# Fuzzy Logic Controller for Hybrid Renewable Energy System with Multiple Types of Storage

by

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Abstract

The objective of this work is to design a scheme to control the power flow of a hybrid renewable energy system with multiple renewable energy sources with the focus on solar energy and wind energy and multiple energy storage systems. The use of energy storage is necessary due to the intermittency of the renewable energy sources and the consequent peak power shift between the sources and the load. In addition, the use of the energy storage can increase the overall system reliability and stability. In this work, batteries are used as the primary energy storage system for short to medium storage term, while hydrogen fuel cell is used as the long-term energy storage. A supervisory control system is designed to handle various changes in power supply and power demand by managing power intermittency, power peak shaving, and long-term energy storage. Since both power supply and demand are not fully predictable and they have time-variant nonlinear behavior, computational intelligence is introduced to solve this issue and provide suitable control algorithm. This type of control, based on fuzzy logic, combines knowledge of the system and control. The proposed methodology can be optimized such that the system is able to adapt to its working environment and deliver best results under given circumstances. For more realistic simulation results, the designed model utilizes real solar and wind power data and house demand data which were collected by smart meters installed in a project done on houses in Alberta, Canada for the year 2016. The model of the system is designed and simulated in MATLAB SimPowerSystems™ environment to verify the effectiveness of the proposed scheme.

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# List of Symbols and Acronyms

| | |
|---|---|
| AC | Alternating Current |
| AESO | Alberta Electric System Operator |
| AUC | Alberta Utilities Commission |
| BSS | Battery Storage System |
| BTU | British Thermal Unit |
| CWEC | Canadian Weather for Energy Calculations |
| DC | Direct Current |
| DG | Distributed Generation |
| DPGS | Distributed Power Generation Systems |
| ESS | Energy Storage System |
| FLC | Fuzzy Logic Controller |
| GHG | Global Greenhouse Gas |
| GW | Giga Watt |
| HAWT | Horizontal-axis Wind Turbine |
| HRES | Hybrid Renewable Energy System |
| K | Kelvin |
| $Km^2$ | Square Kilo Meter |
| KWh | Kilo Watt Hour |
| MG | Micro Grid |
| MPPT | Maximum Power Point Tacker |
| MW | Mega Watt |
| MWh | Mega Watt Hour |

| | |
|---|---|
| NSRDB | National Solar Radiation Database |
| OECD | Organization for Economic Cooperation and Development |
| PV | Photovoltaic |
| RES | Renewable Energy Resources |
| SCADA | Supervisory Control and Data Acquisition system |
| SOC | Battery state of charge |
| TEG | Thermoelectrical generator |
| THD | Total Harmonic Distortion |
| TMY | Typical Meteorological Year |
| VAWT | Vertical-axis Wind Turbine |
| WT | Wind Turbine |

# 1. Introduction

## 1.1 Introduction

Humans started looking for energy sources a long time ago to cover their basic needs of mobility, food, and other requirements such as heating. In the early of 18$^{th}$ century, industrial revolution brought a significant improvement in the human ability to extract more energy from naturally available resources such as oil, coal, and gas [1], because they are cheap, abundant and easy to harvest. However, this way of harvesting energy in 21$^{st}$ century becomes not efficient and scary due to the expansion of energy demand across the globe and the occurrence of global warming and climate change which claimed that extracting and using vast amounts of fossil fuel are the main cause of it. Therefore, finding new energy resources become a need to mitigate global warming and climate change and to supply the huge global demand for energy, which electricity production is a big part thereof. In the recent years, renewable energy resources (RES) are becoming the world focus and grabbing the attention of many governmental organizations. Researchers consider RES the promising energy sources amidst the fear of natural resources depletion and environmental issues such as high level of $CO_2$ and other harmful emissions [2].

### 1.1.1 Global Energy Consumption

The global energy consumption is increasing proportionally as the products that are important for creating a good living standard are being manufactured. Those products entail energy to manufacture, transport and utilize. In addition, industrialization and high-quality services require a high power with an excellent total harmonics distortion, THD%, which increase the global energy consumption. Figure 1 shows that the global energy consumption will rise in the future according to the outlook released in 2016 by U.S. Energy Information Administration [3]. The outlook predicted that the global energy consumption will grow by at least 48% of the current consumption between 2012 and 2040. This growth stems from Asian countries known as non-OECD (Organization for Economic Cooperation and Development) such as China and India and those two countries will be responsible for more than half of this increase [3].

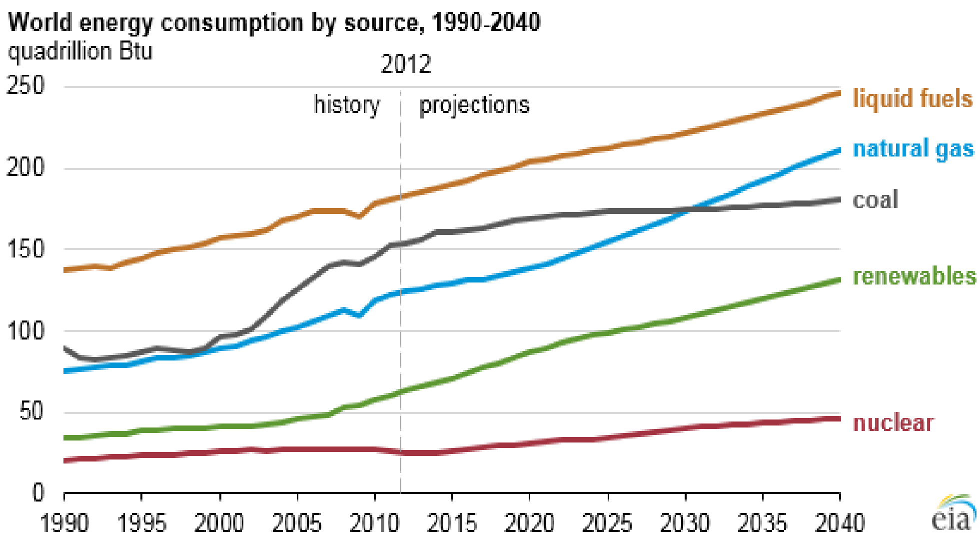


Figure 1-1 World Energy Consumption by Source [3]

There are concerns regarding fossil fuels as energy security, environmental effects, fuel price stability among others. Each of those concerns pushes the policymakers in different countries to start new ways of finding and maintaining renewable energy resources and support programs for both renewable energy resources and nuclear ones. Figure 1 also illustrates the use of renewable energy resources, which is growing rapidly. It is estimated that the growth will be 2.6% each year till 2040. On the other hand, the nuclear energy grows about 2.3% annually [3]. However, fossil fuels still play a major role in the coming global energy consumption and will account for more than three-quarters of that consumption. Coal, which is a part of these fuels, is growing slowly as estimated by 0.6% every year. The new policies on air pollution and reduction in carbon dioxide emissions are the main cause of coal decline in the coming years. China, India and the United States consume 70% of the world total coal consumption [3]. However, natural gas is the fastest-growing fossil fuel due to its low carbon footprint compared to coal and other liquid fuels. It produces 45% fewer carbon emissions than coal when burning for power and 30% less when burning for transportation. It exists in nature in different forms such as tight gas, shale gas, and gas associated with petroleum extraction. The global consumption of natural gas will be increasing 1.9% each year due to increase in the supply of shale gas, tight gas and the gas extracted from coal as it is called Coal-bed methane, CBM [3] [4]. Natural gas generators are usually used in peaking power plants and off-grid systems. High plants' fuel efficiency can be maintained when combining a gas turbine with a steam turbine thereby result in a combined cycle mode [3].

Today, liquid fuels are still the largest energy source to cover global consumption. Nevertheless, in the coming years, their consumption will drop from 33% in 2012 to 30% in 2040 due to various reasons as oil price fluctuation, new more energy efficient technologies and the rise of new clean energy sources with a better economic feasibility as wind, solar and nuclear ones [2] [3].

Another aspect of global energy consumption growth is that global true GDP growth is affecting the energy consumption as discussed by some researchers who relate economy to energy where it is called energy coupling [3]. They compromise GDP of countries from different categories as developed and developing ones with their energy consumption to see how far the country's GDP relate to its own energy consumption. They found as Figure 2 shows the global GDP, in general, has a directly proportional relation with the power consumption. The global GDP is growing 1% more than global energy consumption each year [5]. However, certain countries such as Germany and Japan, their GDP growth doesn't affect their energy consumption.

To illustrate the world future energy consumption, technical experts from the Intergovernmental Panel on Climate Change (IPCC), an organization jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) worked together to model and develop different scenarios. Then, their best most recent scenario is to represent the world energy consumption rate based on fundamental factors according to the following equation:

$$\mathrm{E} = \mathrm{N} \cdot \left(\frac{\mathrm{GDP}}{\mathrm{N}}\right) \cdot \left(\frac{\mathrm{E}}{\mathrm{GDP}}\right) \qquad (1\text{-}1)$$

Where N is the world population, $\frac{GDP}{N}$ is the world GDP per capita and $\frac{E}{GDP}$ is the energy consumption rate per unit of GDP [6]. From the equation, it is shown that as GDP per capita increases and as the population increases the world energy consumption will increase too.

The world population in 2001 was around 6.1 billion people and according to their model, it is projected to reach 9.4 billion by 2050 as a 0.9% increase per year. Also, the world GDP per capita was around $7500 in 2001 and it will go up to $15000 in 2050 with an annual increase of 1.4% each year. The final part of the modeled scenario is the energy consumption rate per capita which was 0.29 W per ($/year) in 2001 and it will reach to 0.20 W per ($/year) in 2050 by a decrease of 0.8% per year. All of these factors are combined together and according to the world energy consumption rate equation, the world consumption rate will increase from 13.5 TW in 2001 to 27.6 TW in 2050 and 43 TW by 2100 according to [6].

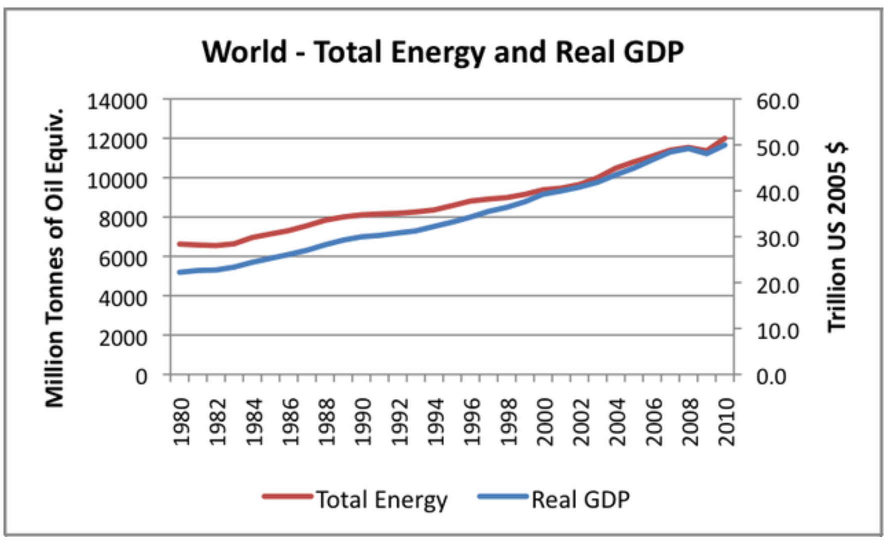


Figure 1-2 World Total Energy vs GDP [4]

Currently, the electrical power generation is still heavily relying on fossil fuel and the use of renewable resources is still in the early phase. The traditional way of generating electricity is to rotate an AC electrical generator using mechanical power where it is mainly generated by the thermal power of burning fossil fuels from coal, oil and natural gas. Oil is the main source of generating electricity in 2010 and the projected oil use to generate electricity is less 10% of by 2030 according to IPCC. Another method of generating thermal power is to use nuclear reactors and according to [7] [8] nuclear power is classified as a clean power if safety procedures followed.

Also, another mechanical power resource is buildings dams to harvest water flow energy which is then used to rotate electrical generators. It is called hydropower which the most used renewable energy nowadays. Many countries with rivers are using hydropower for peak power shaving and fast power response recovery. Global generation of hydropower rises where China retaining the global lead according to Renewable global status report and it shares around 3.6% of total global energy consumption in 2015 and 35.3% of modern renewable energy in the same year [9].

### 1.1.2 Environmental Issues

Besides the huge energy demand due to an increase globally in population and economics, environmental issues are pushing the world to search for better energy resources alternatives and develop technologies to lower their cost and make them affordable for global use. Climate change refers to the issue of global warming or cooling as a result of greenhouse gases (GHG) increase. This change could last for long period of time and could make major changes in rainfall, wind behavior, sea level, precipitation, temperature and other climate patterns. This issue is part of the global change which includes other issues such as ozone depletion and land use change. Climate change occurs from natural factors or human activities. Natural factors are changes in the Sun's energy or changes in the Earth's orbit motion or changes in the ocean circulation. On the other side, human activities affect the atmospheric composition gases as a result of burning lots of fossil fuels, cutting forests, expanding cities and other activities [10]. Therefore, climate change mitigation is an important sector to study the human behavior and contribution to climate change and provide studies and reports to help policymakers in reducing or preventing greenhouse gases emissions, support new different technologies that are less pollutant, and managing consumer behavior [2]. UN Environment is making efforts in order to help countries move towards climate mitigation and low emissions plans. In 2010, the total anthropogenic GHG emissions reached 49 (±4.5) GtCO2eq where from 2000 to 2010 those emissions were the highest in human history [10]. Climate change has implications on different aspects as the following:

1. Energy: Higher global temperature will lead to more air-conditioning usage which increases the electricity bill.
2. Health: Extreme temperatures, as well as irregular weather, could lead to different diseases and sickness.
3. Agriculture and Wildlife: Extreme temperatures, as well as irregular weather, implies lack of proper water supply and worsening crop production which affects food cost and food security.
4. Water Resources: Temperatures as well as irregular weather increase the possibility of flooding and impact the quality and availability of global fresh water supply.

Current energy generation and use are not environmentally and economically sustainable. It requires huge efforts and actions to change to sustainable and low-carbon energy solutions to avoid climate degradation with an average of 6°C. Those sustainable solutions could make significant improvements in social, economic and environmental aspects. It includes but not limited to modern renewable energy, nuclear power and carbon capture and storage facilities (CCS). The global energy-related GHG emissions target is to be 50% in 2050 below today's level [11]. Electricity and heat production accounts for 25% of total GHG emissions in 2010 while the whole energy supply sector is contributing to almost 35% of the global GHG with 14.4 GT of CO2. Therefore, researchers on developing renewable energy harvesting system and technologies are valuable in this decade [10].

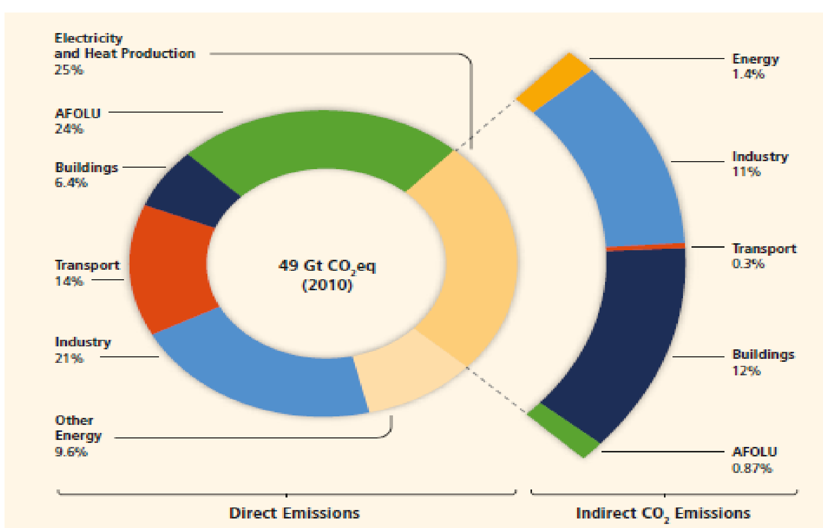


Figure 1-3 Total anthropogenic GHG emissions(GtCO2eq/ yr.)by economic sectors [10].

## 1.2 Objective of the Thesis Research

The objective of this research is to design a stand-alone power system to supply uninterruptible high-quality power to a medium size load such as a house. According to Statistics Canada, the average household electricity use 30 kWh/day that is 40 gigajoule per year [12]. Therefore, the proposed system has a maximum peak power capacity of 10kW for more reliable and consistent power and able to cover the need of 30kWh/day house in Canada. The input power to the system is achieved by harvesting hybrid renewable energy resources as sunlight using photovoltaic technology and wind flow using medium size horizontal wind turbine under variable weather conditions. For best performance, two types of energy storage are used to achieve power stability, reliability, and great power quality. The first energy storage is a battery bank which will be the direct medium for extra power storage or needed power direct supply. The second system is a full hydrogen fuel system which supports the battery to work smoothly and stand by the battery when the load is huge or when it is critical for the battery to handle the load alone. Also, it operates as an energy reservoir for long strategic energy storage. However, in order for all these subsystems to work in harmony and achieve the proposed goals, the supervisory controller is the key for such hybrid system. Therefore, the main controller with the certain algorithm is established to manage the power flow between those subsystems. Different methods of controlling have been conducted by researchers and we design our controller algorithm to have a new way of looking at the system, introduce new considerations and to fill a gap between previous research techniques.

## 1.3 Methodology

To have an idea about designing a power management controller for a stand-alone Hybrid Renewable Energy System (HRES) with multiple types of energy storage using fuzzy logic, several journals' papers, books, statistical and technical reports, white papers and web articles are required to be read and reviewed. Based on this general review of different fields, a large amount of knowledge needs to be processed and used in the research that is to be conducted. Then, the thesis will be formed by initially having a general introduction to the topic and providing full background about the sub-systems that are involved in the HRES. Those subsystems are approached theoretically by understanding the related concepts and systemically by modeling and simulating in Simulink MATLAB. After designing each subsystem model individually, several simulations are done to make sure the model responds correctly and will function properly when connected to the other systems. After that, the data collection and system optimization and sizing are to be considered. The final step is how the proposed new controller design will defer from previous researchers' work and which gap it fell. After finding a suitable point to search about and having a knowledge of using fuzzy logic in system management, the controller is proceeded block by block using the Simulink MATLAB and then tested. This model will be then connected to all subsystems designed previously to run several simulations and discuss the outcome results.

## 1.4 Structure of Thesis

This thesis is organized into six chapters. The first chapter is a general introduction to the thesis which includes general information about energy, global energy demand and introducing the motivation of using renewable energy resources and developing control systems that can manage the power flow of such nonlinear weather dependent systems in order to maintain high power quality and stability. Also, this chapter introduces the objective and goals of the thesis and the methodology of conducting the thesis work. After that, a separate section for the structure of the thesis is shown. The second chapter gives the reader a solid background and state of the art for the hybrid renewable energy systems and introduces each component in a separate section. It starts with renewable energy resources followed by energy storage methods. Then, the hybrid energy system is introduced as its definition, different system configurations, smart grid concept and other crucial elements such as power converters.

Chapter three is more about the methodology of designing HRES and its controller using the Fuzzy logic method. It starts by collecting data for solar and wind subsystems. Then how the whole system to be sized then how other research works have different goals and approaches then how the proposed system has its own goal to fill a gap between researchers and enrich the literature for coming researchers and give them a new to look at the system and its dynamics.

Chapter four starts with an introduction to fuzzy logic from a theoretical point of view and how fuzzy logic works. The second section talks about implementing fuzzy logic in control and some examples of successful fuzzy control projects. The followed section talks about some fuzzy controller applied in the field of energy systems then our proposed fuzzy algorithm is introduced with details.

Results and discussions are then taking place in chapter five where different scenarios facilitate a comprehensive evaluation of the new method, several cases are considered progressing from the charging mode to the discharging mode in the presence of fluctuating solar and wind power and then their results are discussed. Chapter six gives a major conclusion for the thesis and also some future development and recommendations.

# 2. Background and Related Work

## 2.1 Renewable Energy Resources

Renewable energy is an energy that can be harvested from natural renewable resources and it is sustainable and abundant compared to human lifespan. For example, solar energy can be harvested by converting its solar irradiance into either heat or electricity depending on the technology used. Wind, hydropower, tide, biomass, geothermal are also different examples of renewable resources. Renewable energies have enormous potential globally due to many concerns and factors. They pollute less than fossil fuels, exist almost everywhere and could have higher total efficiency as the energy harvesting and conversion technologies getting improved. Also, the global demand growth and the rise of smart grid concept push more on selecting those sources rather than traditional ones. In this Section, the focus will be on solar and wind energy resources because they are selected as a part of the studied hybrid renewable energy system model.

Solar and wind are chosen because of their availability almost everywhere on earth compare to other renewable resources such as hydropower and geothermal which occur in some places in the world and not others depending on geographical features. Also for off-grid system application, it is better to have portable, easy to transport, easy to install and compact system as solar photovoltaic panels and wind turbine do. As well, wind power generation became the second largest renewable power in 2016 after hydropower with a power capacity of 487 GW compared to 433 GW in 2015 [9]. Where solar PV took the third rank with a power capacity of 303 GW in 2016 as an increase of 32.9% compared to solar PV capacity in 2015. In addition, the new installed solar PV in 2016 represents 47% of the new installed renewable power in 2016 [9].

many other reasons that encourage using solar and wind to assuring sustainable future generations life, reducing greenhouse emissions such as nitrogen oxides ($NO$, $NO_2$ & $N_2O$), sulfur oxides ($SO_2$ & $SO_3$), and carbon oxides ($CO$ & $CO_2$) and increasing energy sources diversification. The $CO_2$ emissions for solar PV are estimated to be 49.91 g on average with a low estimate of 1 g and a high estimate of 218 g per kWh while wind $CO_2$ emissions are 34.11 g on average with a low estimate of 0.4 g and a high estimate of 364.8 g per kWh [13].

### 2.1.1 Solar Energy

Sun is the primary source of most energies on earth. It rises to the sky everyday carrying lots of energy to heat and light the earth surface. It is the only star in our solar system and the nearest one that can supply a tremendous amount of energy to our home, earth. It is almost 99.85% of the total mass of the solar system. The average distance between sun and earth is 150 million km and sunlight needs eight minutes and 20 seconds to reach earth [14]. Theoretically, the sun's power over earth surface is 89,300 TW [6]. Sun is powered by nuclear fusion of hydrogen atoms and its surface temperature reach 5,800 kelvins while its core reaches a high level of 15.7 million K [15].

When the sun rises, the sunlight energy is either reflected or absorbed. Around 51% is absorbed by land and ocean and 16% by the atmosphere which heats up earth and makes it suitable for all living species. On the other side, 20% is reflected by clouds, 6% by the atmosphere and others [6]. Plants are the oldest solar harvester which harvests the sunlight and convert it into chemical energy in the form of sugar and produce oxygen because of a process called photosynthesis [16].

For a long time, people looked at the sun as a great source of energy and they started thinking how to convert that energy into useful forms. One of the trivial methods started by concentrating solar power into a focal point to cook food and the first reported solar cooker was in India in 1878 by Adams [17]. Heating water up, distilling water or purring water using solar power can be added to the list.

In late 20$^{th}$ century, with the increase of fossil fuel price fluctuation, the rise of global warming and the need for energy security, many governments, industrial holders, scientists and engineers took in consideration developing new technologies and methods to harvest solar energy resource and generate electricity as a renewable, clean, and sustainable power source.

Technologies went in different directions as some scientists and engineers focused on converting sunlight into heat and then into electricity while others prefer direct conversion. One big achievement in today's solar energy field is the photovoltaic cell that is a semiconductor material which converts light into electricity based on a physical principle named photoelectric effect [10]. Other semiconductor materials can convert solar heat into electricity where this process is called thermoelectrically generation (TEG). However, it is still in its early ages since some scientists work to increase their efficiency and decrease their production cost [18]. Both power conversion cells are solid state and direct energy converters that's account for quiet operation with no moving parts and less maintenance. On the other hand, solar thermal power takes a much longer process and requires more various parts to achieve electric power generation.

#### 2.1.1.1 Sun Energy form

Sun energy comes to earth in the form of electromagnetic radiations with different wavelengths [19]. It follows this distribution: 6.6% ultraviolet, 44.7% visible light and 48.7% infrared as shown in the figure:

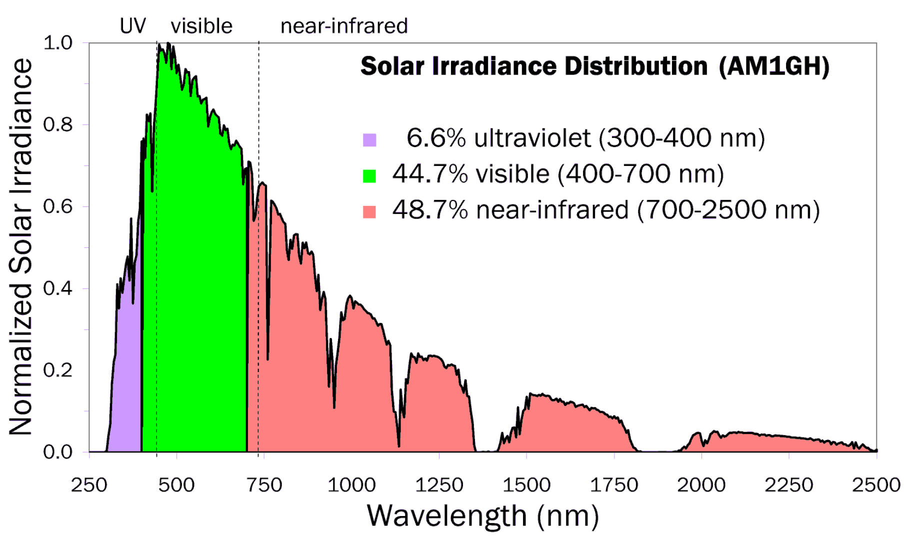


Figure 2-1 Solar energy distribution [9].

### 2.1.1.2 Sun Energy Harvesting techniques

There are many techniques nowadays to harvest solar energy and convert it into useful power or electrical power specifically. For electrical power application, solar energy can be harvested using photovoltaic or solar thermal technologies and in this thesis work, photovoltaic technology is selected because such technology plays an important role in the renewable energy industry, solar type. It is nominated to be the first choice for investors compared to concentrated solar power (CSP) and other technologies due to its cost competitive, low maintenance, easy installation, compatibility, noiseless and direct energy conversion. In 2016, China alone accounts for 85% of the total Solar PV installation worldwide [20]. The next figure classifies different solar technologies according to their working principle.

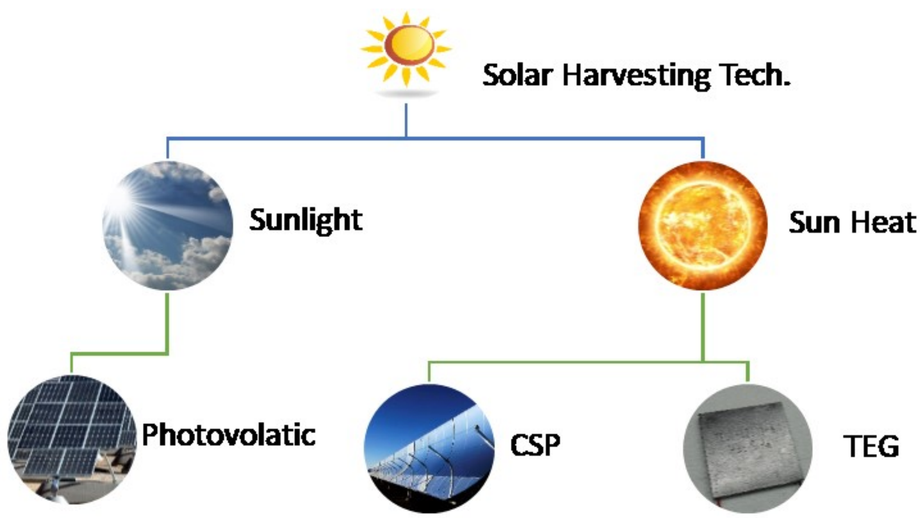


Figure 2-2 Solar Harvesting techniques

### 2.1.1.3 Photovoltaics

A photovoltaic cell is a semiconductor material that converts light directly to electricity based on the principle of photoelectric effect [21]. The first photoelectric effect discovered by French physicist Edmund Becquerel in 1839 [10] where he observed it in Selenium [22]. Photovoltaic cells consist of two or more layers to create a permeant electric field. When light strikes the cell, electrons get excited and make their way to the conducting part of the cell to the load [10].

The solar irradiance and ambient temperature are the PV cell's inputs whereas electrical current and voltage are the cell's outputs. The commercial PV cell has very low conversion efficiency with an average around 12-17%, and where a super-mono cell has an efficiency of 21% as shown in the figure [23]. Since those cells have lower efficiencies yet and they are weather dependent and have nonlinear output power, extracting the maximum possible power is an essential aim for a powerful PV system.

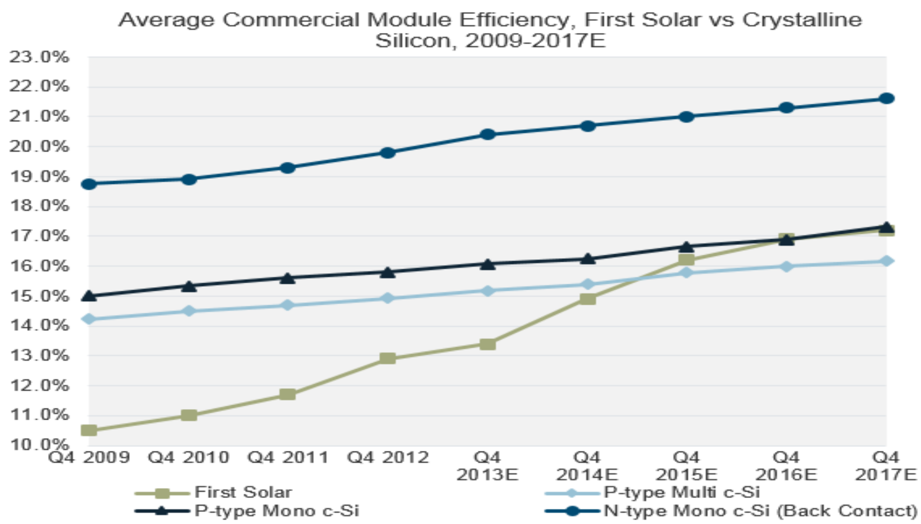


Figure 2-3 Average Commercial PV Efficiency [23]

The next figure describes the characteristic of a PV current and voltage. Thus, the cell current is proportional to solar irradiance while its voltage is inversely proportional to ambient temperature [24].

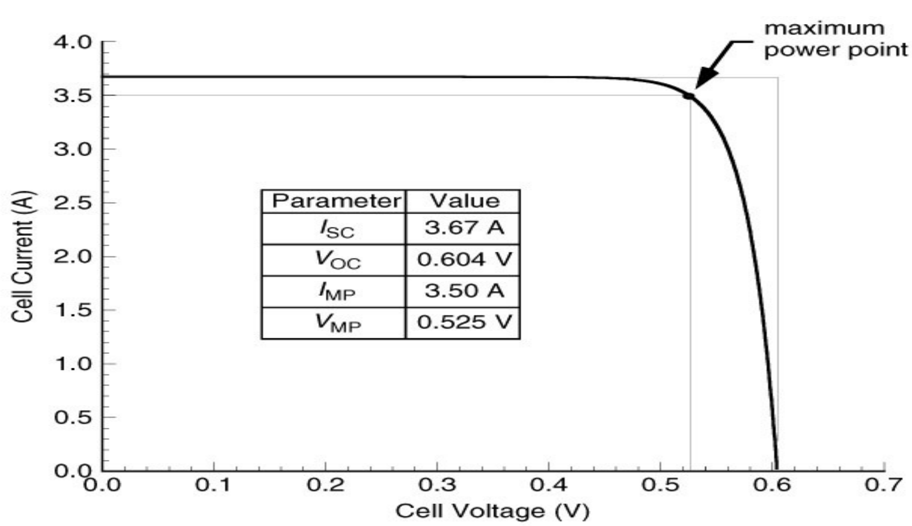


Figure 2-4 Current-Voltage characteristic for PV cell [24].

The PV cell converts light with different wavelengths into the current at the PN junction, producing electricity directly from the cell when connected to a load. According to [25] the current produced is given by

$$I_{total} = I_0(e^{qV/kT} - 1) - I_L \qquad (2\text{-}1)$$

where $k$ is Boltzmann's constant, $I_0$ sets the current scale and $q$ is the electric charge of the particles which comprise the current $I_{total}$. Also, $I_L$ is the light generated current, and $T$ is the ambient temperature. Based on the solar irradiance and the ambient temperature, which are two crucial physical quantities in PV technology, the PV cell corresponds to and produce open circuit voltage and closed circuit current [25].

Extracting the maximum available power can be done by monitoring the maximum power point on the PV curve under varying operating conditions such as irradiance changes (partial shading), temperature changes and load changes. This monitoring mechanism determines the best system's voltage value and it is done using maximum power point tracker MPPT. The MPPT is the medium between PV arrays and the rest of the power system. It consists of a dc-dc power converter and a control that observe PV current and voltage and based on certain algorithm adjust the duty cycle of the dc-dc power converter. Researchers have been developed different approaches and techniques to design this algorithm. Some of those algorithms in those papers [26], [27], [28].

The generic Solar PV system consists of Solar arrays, MPPT controller, and a DC-DC power converter as shown in the next figure [29]:

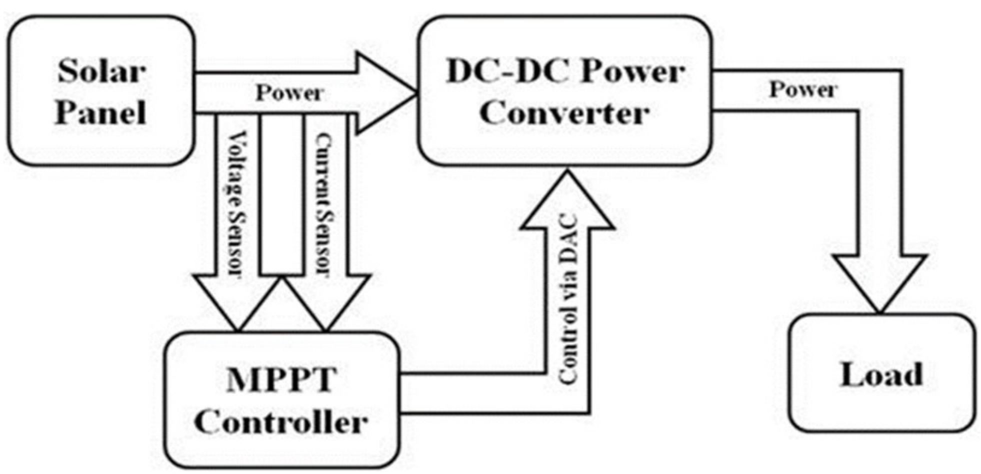


Figure 2-5 Solar PV System Components [29]

### 2.1.1.4 Concentrated Solar Power

Concentrated solar power, also known as solar thermal electricity (STE) is the process of concentrating solar radiation and uses its heat to heat a fluid that runs a steam turbine to drive an electrical generator. It is another way of harvesting solar irradiance. The sun heat is collected and concentrated to heat up a fluid either liquid or gas, normally oil or molten salt then that fluid runs through a heat exchanger to transfer the gained heat to boil water to drive a steam turbine. In some plants, the remaining fluid can be stored in a thermal storage unit for later use. The steam turbine is connected to an electric generator to generate electrical power to the system. The system is either the grid-connected or an off-grid. In practice, CSP maximum temperature reaches over 1000 °C with a concentration factor of over 10000 [30]. In 2016, the total CSP power generation jumps to 4.8 GW, where Spain is the market leader with 2.3 GW generation followed by United States which produces 1.7 GW as shown in the following figure [20].

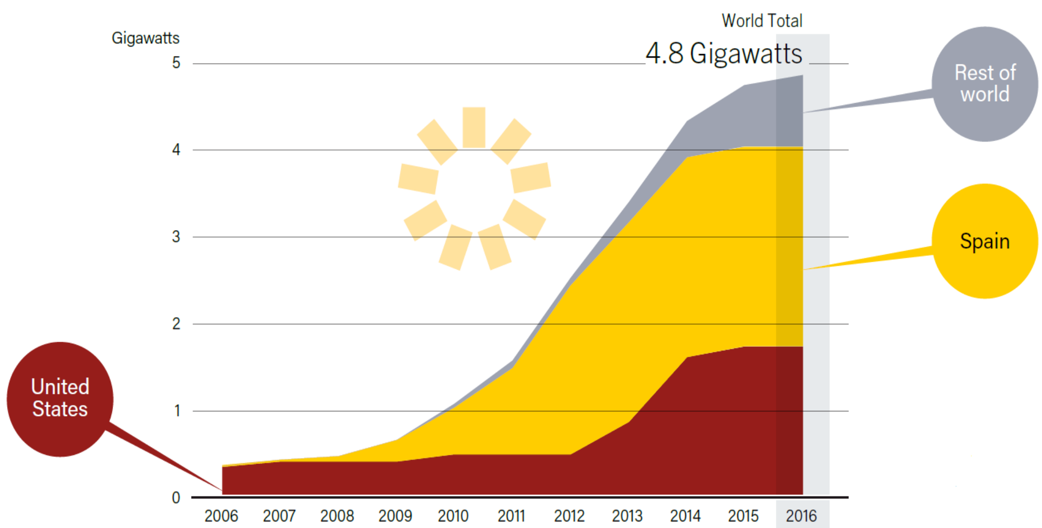


Figure 2-6 Concentrating Solar Thermal Power Global Capacity [20]

Different types of CSP, as well as different configurations, exists. CSP has four major types of Linear Fresnel reflector (IFR), Parabolic trough, Central receiver, and Parabolic dish. The first two types are called single-axis concentrators where the sunlight is concentrated onto an absorber tube. Whereas the other two types are called dual-axis concentrator where the sunlight is concentrated on central absorber at the focal point. Both kinds require solar tracker that senses the sun position in the sky and then adjust the concentrator accordingly for optimal power generation [30]. The next figure shows the four types of CSP [31]:

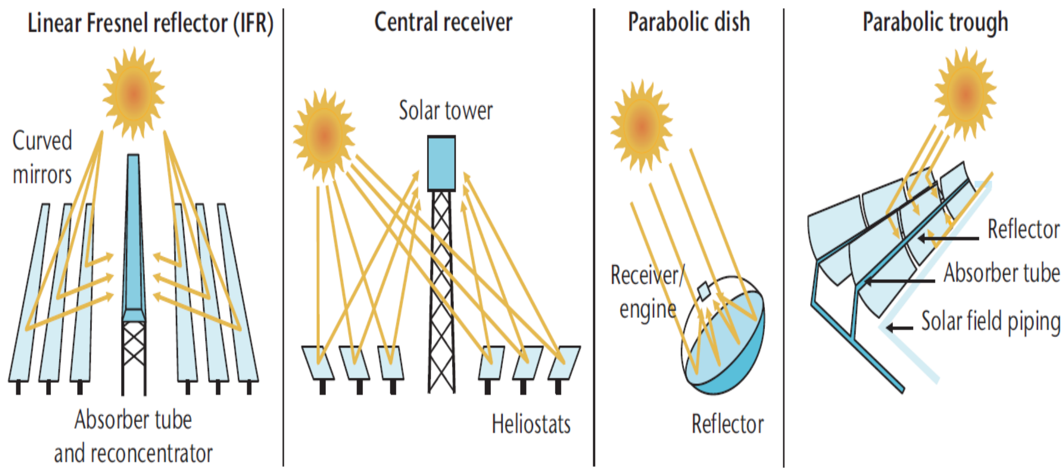


Figure 2-7 CSP Main Technologies [31]

Most current CSP projects use thermal storage units to store extra heat and supply it to the system when demand is higher than supply. In addition, most common types used are the parabolic trough and the central receiver techniques [30].

### 2.1.1.5 Thermoelectric Generator

Seebeck effect is a physical effect that illustrates the conversion of heat into electricity at the junction of two different materials mostly appear in conductors or semiconductors due to movement of charge carries, Thomas Seebeck discovered that effect in 1821 [18]. TEG stands for thermoelectric generator. For many years, researchers focus mainly on developing thermoelectric materials from semiconductor materials for several reasons:

1. They have a low thermal conductivity that reduces the heat flow from the hot side to the cold side.
2. They have high Electrical conductivity especially at high temperature and that increases the power factor of the material since the power factor is $P = \alpha S$ where S is the Seebeck coefficient.
3. They have excellent electrical band structure compared to metals.

TEG works under tough conditions as high temperature on the hot side and a low one on the cold side which could result in stress and strain on the device. On the other hand, the cell produces small voltage due to geometric limitations so the best design avoiding these constraints is connecting the cells electrically in series and thermally in parallel. The following figures describe how it works [21]:

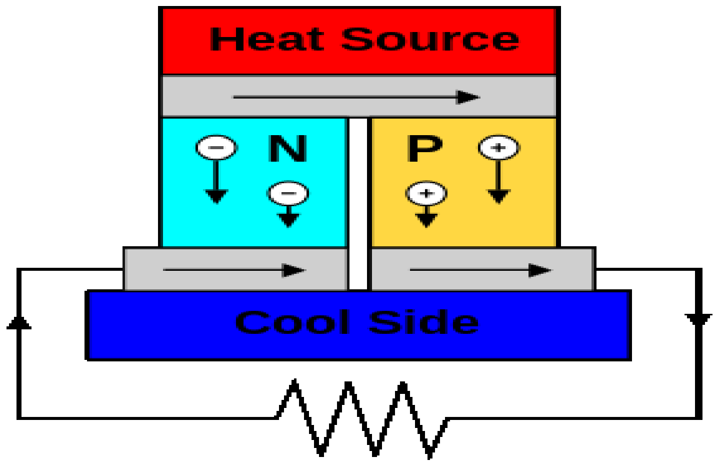


Figure 2-8 Charge Movement in Thermoelectric Cell [21]

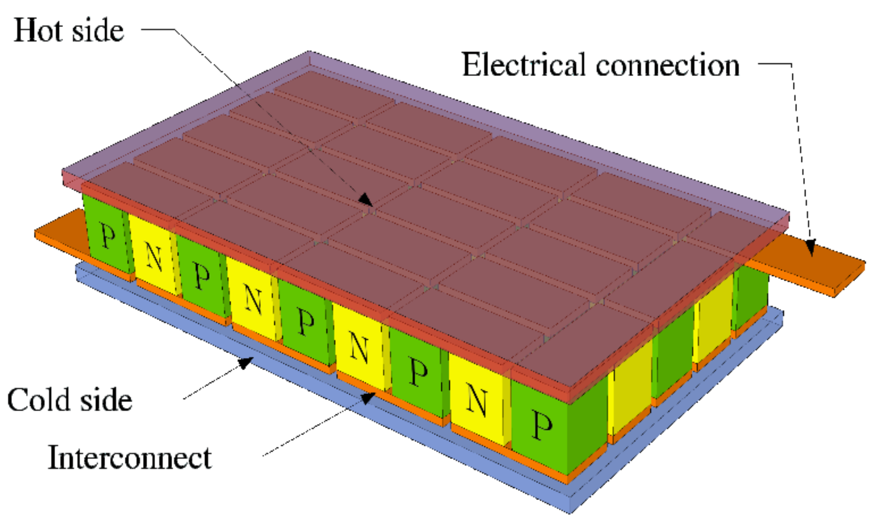


Figure 2-9 Thermoelectric Generator Module [21]

There are three famous materials used for TEG, Bismuth Telluride (Bi2Te3), lead telluride (PbTe) and silicon germanium (SiGe). Most typical TEG has an efficiency of 5-6% [21].

$$ZT = \frac{electrical\ conductivity * temprature * s\string^2}{Thermal\ conductivity} \quad (2\text{-}2)$$

Existing TEG applications are many such as heat waste recovery in an automobile, power plants, and gas pipelines where the Gentherm company is the world's largest manufacturer of TEGs [32]. Also, spacecraft use radioisotope TEG for power generation as in the spacecraft that sent to Saturn, Cassini-Huygens, which has three radioisotopes TEG fueled by 238Pu (Plutonium) and the thermoelectric material used is SiGe [33]. However, this technology still has major drawbacks to use as:

1. The materials used are rare elements, therefore, they are expensive to get and require high purification process for great efficiency.
2. Current efficiency is still low compared to other technologies.

So the solution to these obstacles can be overcome by using thermal collectors, hybrid design, creating new material and Nanostructured ones.

Since the cost of TEG is high, it is efficient to use solar thermal collectors to increase the hot side temperature and reduce the size of TEG material. In addition, effective heat dissipation materials are used to have a large temperature gradient. There are two main types of solar thermal collectors: optical light concentrator and thermal absorber. A lab experiment uses thermal absorber with solar absorptance of 94.4% to make a flat CTEG panel and the results were shocking, they were able to increase the efficiency by 7-8 times (4%) by using a p-type ZnSb alloy and an n-type Bi-base alloy with an efficiency of 0.5% and they claim the efficiency can get higher than 15 times (8%). many factors lead to such a result: nanostructured materials, selective surface, high thermal concentration, Operation in an evacuated environment [34].

### 2.1.1.6 Solar Thermoelectric Generator Vs Concentrated Solar Power

Both are heat engines and follow Carnot principle. They are designed to convert solar thermal into electricity as a power system. STEG is noiseless, no moving parts, direct conversion, depends on material properties, very low maintenance, robust –solid state, works for any temperature gradient, operates in zero gravity, size highly scalable, can be small size. However, it is costly, has low efficiency and low potential market.

On the other hand, CSP has working fluids, moving parts, multi-component system, require regular maintenance, depends on material and system, usually for large systems application, uses existing industrial base, and limited geographical locations due to federal and environmental regulations. However, it is effective, especially with high concentration ratios and storage elements.

### 2.1.1.7 Photovoltaics vs Concentrated Solar Power

According to NREL, the most powerful photovoltaic cell tested in the labs has an efficiency of 46% at Fraunhofer ISE labs [35]. However, the highest commercial photovoltaic cell has an efficiency of around 21% [23]. PV has three major types of monocrystalline, multi-crystalline and thin film plus other minor ones.

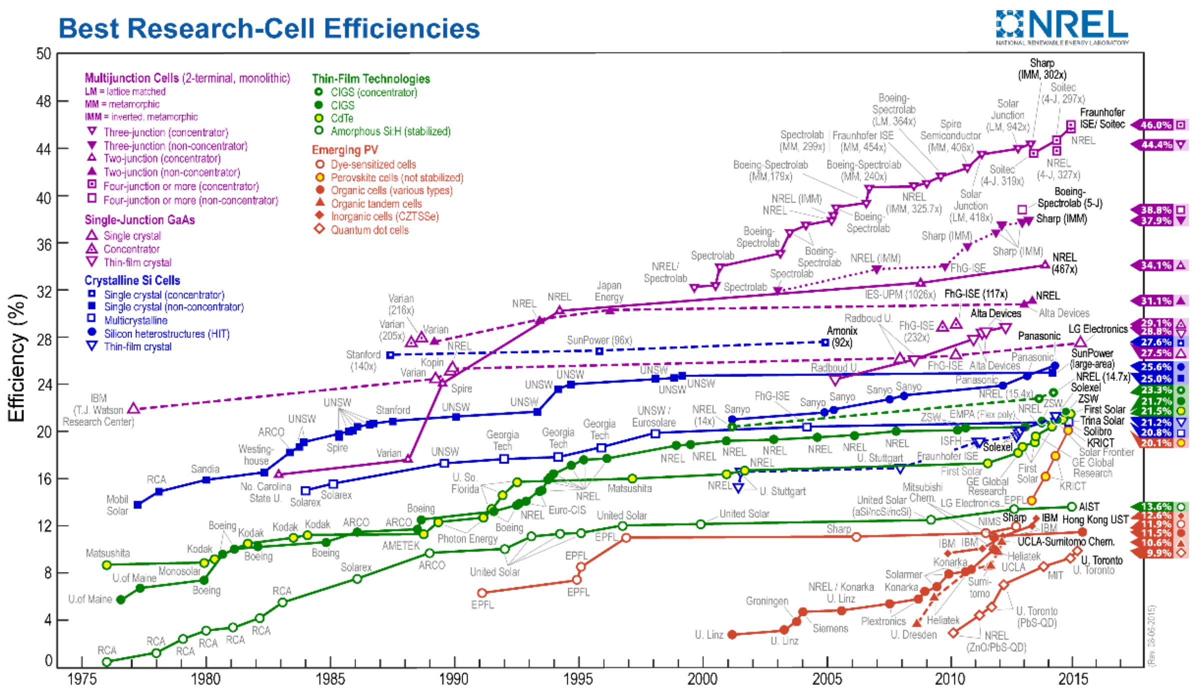


Figure 2-10 Top Research PV Cell Efficiencies [35]

On the other hand, concentrated solar power technology works as a heat engine and convert heat into work and follows Carnot's principle so their efficiency depends on concertation factor and the receiver temperature. The best commercial efficiency is around 49% for molten salt tower plus project according to Abengoa company where it is shown in next figure and compared with combined cycle efficiencies [36]. CSP in sunny regions produces electricity cheaper than Solar PV [30].

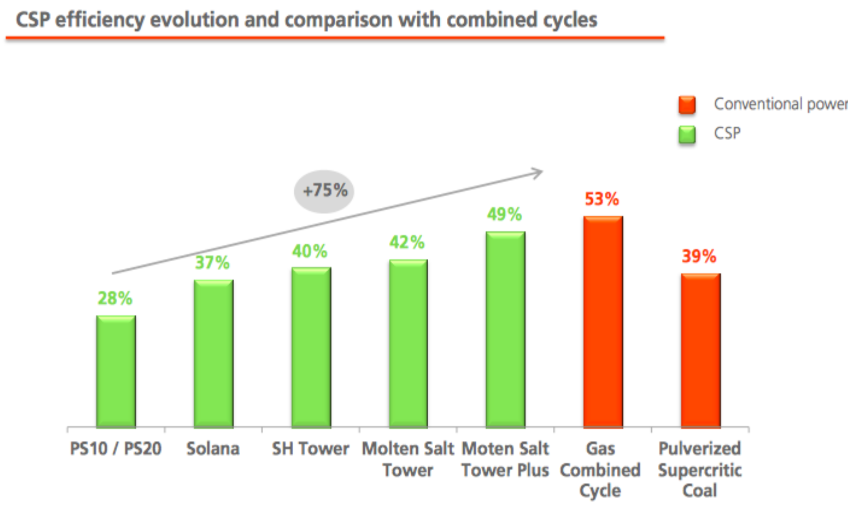


Figure 2-11 CSP Efficiency compared to combined cycles [36]

### 2.1.1.8 Hybrid Photovoltaics and Thermoelectric Generator

Synergy principle states that merging different resources, components, will lead to higher work efficiency and that gives many researchers a potential of making hybrid renewable energy sources, so each source would complement the other and result in a highly efficient system.

PV and TEG have a lot of similarities which helps designers to build systems containing them for better output power quality and efficiency. Both of them are noiseless, scalable, depend only on materials and produce direct electricity. Some researcher did a great job of designing and analyzing such systems.

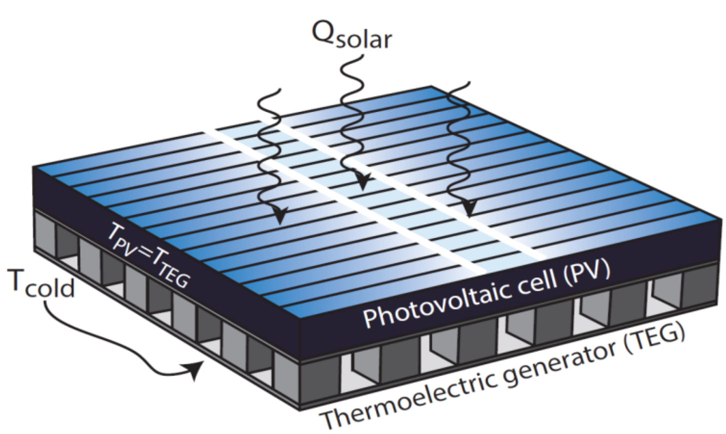


Figure 2-12 Hybrid PV-TEG Cell [37]

Through many types of research the total PV plus TEG power output will increase with solar thermal collectors but without them, the total efficiency could be lower than stand-alone PV. PV converts part of the spectrum into electricity and the large part becomes heat so one research uses a wavelength separator to pass up to 800 nm to the PV while reflecting the rest. This graph illustrates the idea of the separator [37].

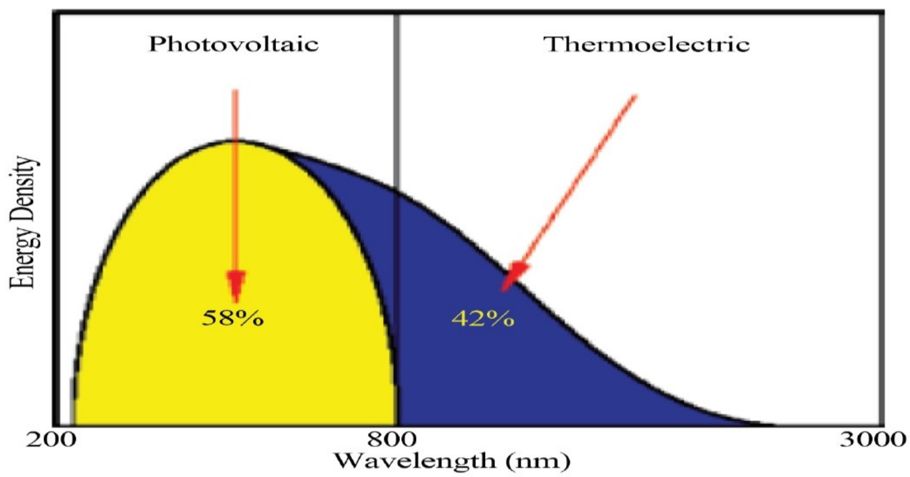


Figure 2-13 Solar Radiation Spectrum Separator [37]

Another study shows that certain PV types are good to merge with TEG because of their thermal properties. The TEG must have maximum operating temperature under 200 Celsius otherwise the PV efficiency will decrease rapidly and so the total efficiency [37].

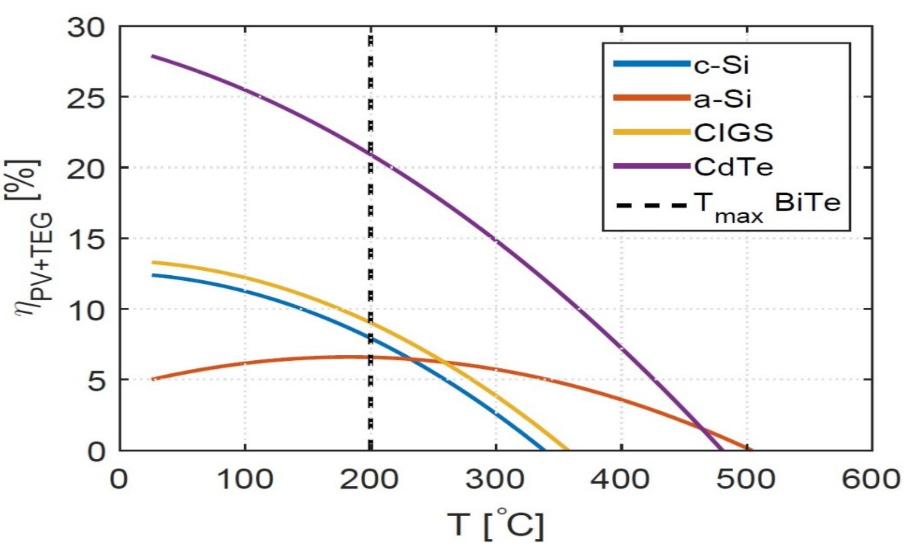


Figure 2-14 PV+TEG Cell Efficiency [37]

## 2.1.2 Wind Energy

In recent years, wind power generation has a great potential worldwide even greater than solar photovoltaic technology and it is one of the worldwide fastest-growing renewable energy [10]. By 2016, the world wind power generation was 487 GW with an increase of 55 GW compared to 2015. The top five countries in wind power generation are China, United States, Germany, India, and Brazil. Over 90 countries have commercial wind power generation and 29 of them exceed one Gigawatt capacity in 2016 [20]. With current policies, the estimate power generation would reach 977 GW in 2030 [38]. The first inspiration to use a windmill to produce electricity was in Scotland in July 1887 by Professor James Blyth of Anderson's College who designed a 10-meter-high windmill and was installed in his holiday cottage garden [39].

Wind is the flow of air mass as a natural phenomenon due to differential atmospheric pressure. The differential atmospheric pressure forces the air to move from higher to lower pressure area. The differential is generated via differential air temperature and earth surface terrain. Sun heat is reflected from earth's surface to the surrounding air and since sun heat is not distributed equally on earth the differential air temperature is created which leads to wind creation [40]. Therefore, winds have different speeds directions and patterns as the next figure shows how winds circulate around the earth [41].

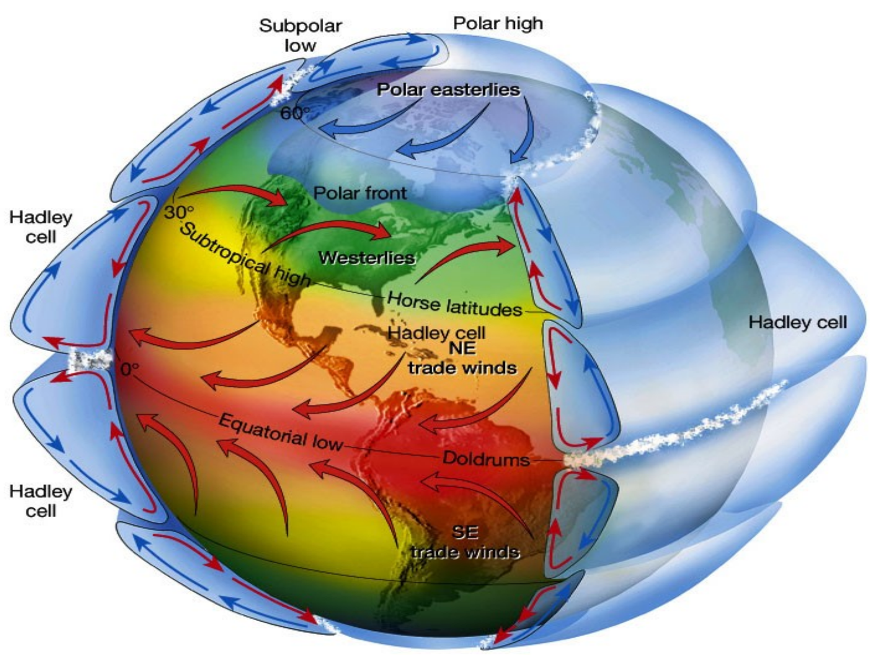


Figure 2-15 Global Circulation of Winds [41]

The wind has been used by human long time ago to move their sails which makes sailing possible at that time. Also, in rural communities, wind drives windmills to pump well water to the earth's surface as well as some windmills are used to grind grains as the Dutch windmill on the Danish island of Bornholm which is shown in the next figure.

Figure 2-16 Dutch windmill on the Danish island of Bornholm (*CC BY 3.0*)

Nowadays, as the world is hungry for energy and wind is available free renewable everywhere so the chance of harvesting wind and funding wind turbines projects is profitable and worthy. In the 1970s, the world became more interested in wind power and started developing some wind turbines. There were reasons for this interest. Oil price inflated in the mid-1970s in contrast with the advancements in materials, aerodynamic analysis, and computer-aid software. Those reasons gave the birth to develop and establish vast amounts of wind farms [42].

Later, wind turbines become more popular and investment attractive because of its high-power output per unit and the usage of the old technology of Electrical power generators. In addition, they are low maintenance, use little land, robust, have direct power conversion, low noise and uses existing power infrastructure such as transmission lines. However, they have three drawbacks. First, power output is difficult to control. Second, wind farms are better for peaking applications. Third, sufficient wind speed has to exist so wind turbine can produce power and this speed is called cut-in speed [10].

There are two types of wind turbines horizontal-axis and vertical-axis and in this thesis work, the aim is to focus on horizontal type due to many reasons such as horizontal turbine is more powerful and easy to cut-off at very high wind speed and the data collected is from real horizontal wind turbines located in Alberta, but horizontal wind turbines require yaw control to face the wind direction. Wind turbines are very scalable, so large ones can be used to power a grid while others are suitable for small scale as a farm or even a street lamp. However, most investors seek bigger ones because they generate more power with less cost per unit.

Horizontal-axis wind turbines (HAWT) which the most commercial type has the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind which requires yaw control. Then, the rotors blades rotate vertically and harness wind power into mechanical power explained by laws of aerodynamics then drive an electric generator. On the other hand, the vertical-axis wind turbines (HAWT) have the main rotor shaft vertically and the generator is beneath it. The rotor rotates at very low and high speed which gives this type wide range of operation. Also, the rotor is not required to be facing wind and wind from various directions can be harvested. Next figure designed by American wind energy association [43] shows the difference between HAWT and VAWT:

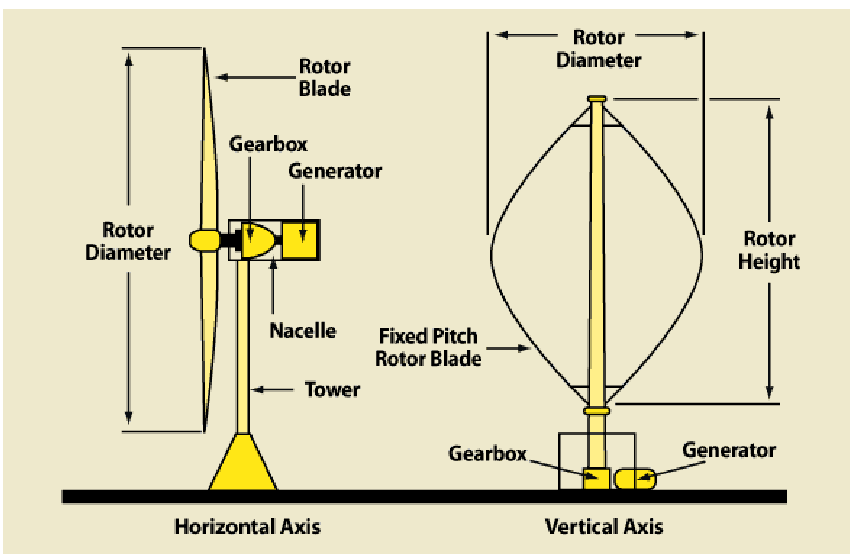


Figure 2-17 Horizontal-axis and Vertical-axis Wind Turbines [43]

The basic components of a horizontal-axis wind turbine are three as a rotor, nacelle and a tower. The rotor which is approximately 20% of the wind turbine cost [38] consists of a group of blades usually three but can be two or more and those blades receive wind and convert wind power into mechanical power according to the equation:

$P_{eff} = C_p \eta_{gear} \eta_{gen} \eta_{ele} P_w =$ [redacted] $(\eta_t \rho A \bar{u}^3)$ (2-3)

where $P_{eff}$ is the percentage of the rated output, $P_w$ is the mechanical power in the moving air, $\rho$ is the air density, $A$ $is$ the area swept by the rotor blades, and $u$ is the velocity of the air. Accordingly, Betz's law gives the maximal achievable extraction of wind power by a wind turbine as 59.3% of the total kinetic energy of the air flowing through the turbine [34].

The second part is the nacelle which houses and protects mainly the mechanical and electrical components. The first component in the nacelle is a gearbox which converts low wind speed to suitable high speed for generating electricity. The generator is the second component which is approximately 34% of the wind turbine cost generates electricity at certain ac frequency [38]. The third component is the controller which controls power conditioning and rotor breakers. The final part is the tower that holds the nacelle and the rotor. It includes rotor yaw drive and motor and accounts for approximately 15% of the wind turbine cost [38]. More details about wind turbine components are illustrated in this figure [44]:

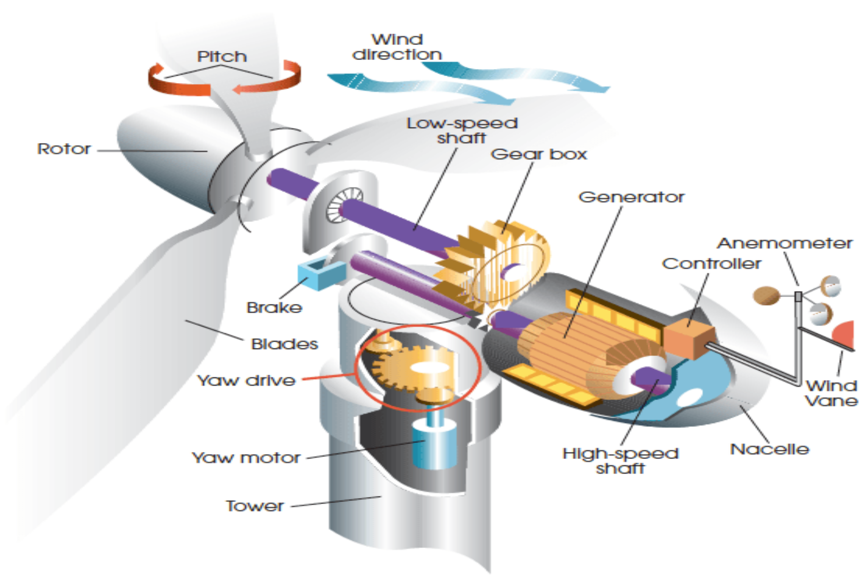


Figure 2-18 Wind Turbine Components [44]

The typical wind turbine has a power output proportional to wind speed. Wind speed controls the power generated and most typical wind turbines have cut-in wind speed where no output power generated and as the wind speed increases the output power increases as well. However, this increase will stop at certain wind speed and the output power remains steady. This speed is called rated output speed. The cut-off wind speed occurs when the turbine can't operate safely beyond this speed. The output power is proportional to the cubing of the wind speed and to the dimensions of the rotor. Theoretically, when the wind speed is doubled, the wind power increases by a factor of eight. Overall efficiency is typically from 30 to 40% and most today's turbines are designed and built to commercial utility-scale where the average turbine rated at 2 to 3 MW capacity [28]. The following figure describes the relation between output power vs wind speed [45]:

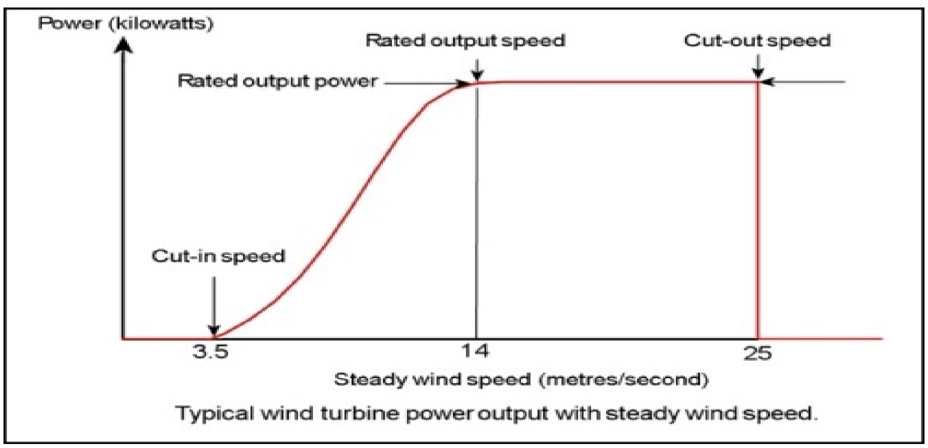


Figure 2-19 Output power vs Wind Speed [45]

In general, wind generation is defined by three characteristics as:

- wind turbine type either horizontal-axis or vertical-axis.
- onshore or offshore installation.
- grid connectivity either connected or stand-alone.

Wind turbines are becoming bigger and more powerful. Their size is continually growing for economic and environmental reasons. The average size of an onshore grid-tie wind turbine rose from 0.05 MW in 1985 to 2.0 MW in 2014 while the largest wind turbine up to date has an 8.0 MW power capability with a rotor diameter of 164 meters [38]. Dong energy is one of the pioneer company in wind industry designed a figure to compare wind turbine sizes with a Boeing 747-8 as shown in the following figure:

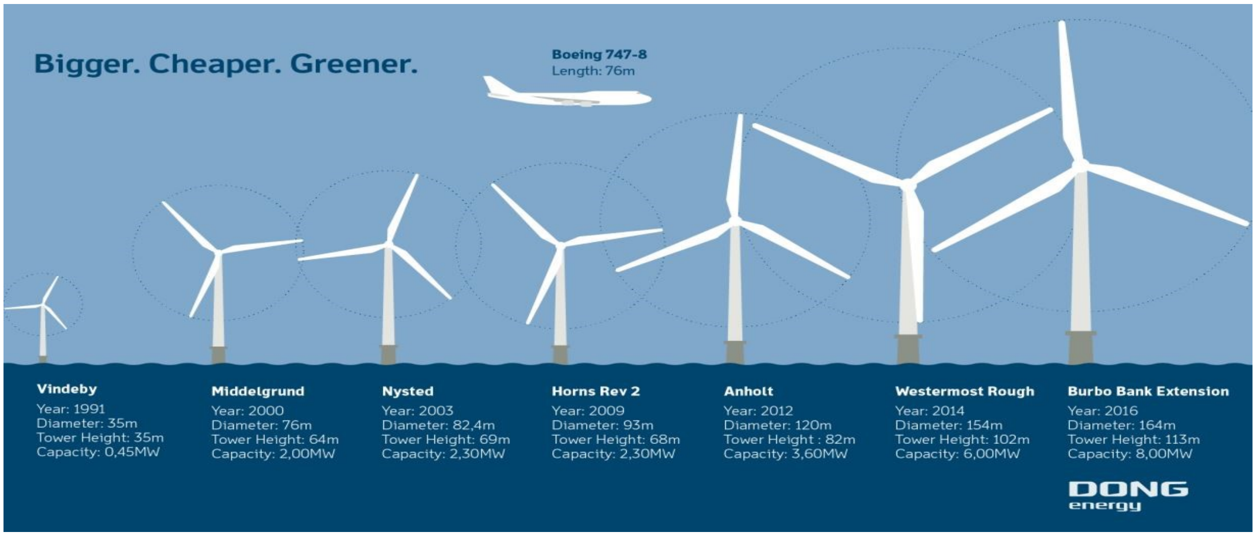


Figure 2-20 Several Commercial Wind Turbines Sizes (credit for *DONG Energy*)

## 2.2 Energy Storage Systems

Supply is most of the time not matching the demand and it is worse in the case of renewable power generation since power generation as a supply is nonlinear and time variant all the time because the power availability is reliant on weather conditions. As a result, power intermittency and power shaving occur and cause challenges to the system which affect power quality, reliability, and robustness. As a result, when the supply power is higher than demand, the extra power is lost unless there is a way to store and vice-versa scenario when demand is higher than supply power extra power needed to be in the system otherwise the system will shut down and cause a blackout. Therefore, having a storage system as a medium to store extra surplus power and release it when needed and smoothing output power is vital in modern renewable power system design. However, there are diverse ways of storing energy in different forms. Those forms are mechanical, electrical, chemical, thermal and electrochemical. The following table illustrates those diverse types with some examples [46]:

**Table 2-1 Electrical Energy Storage Types**

| Mechanical | Electrical | Chemical | Thermal | Electrochemical |
|---|---|---|---|---|
| Pumped Hydro<br><br>Compressed Air<br><br>Flywheel | Double-layer Capacitor<br><br>Superconducting magnetic coil | Hydrogen Fuel | Sensible heat Storage as molten salt | Secondary batteries<br><br>Flow batteries |

Most electrical storage system has three essential components as power transformation system (PTS), central storage and charge-discharge control system (CDCS) [42]. Different types of electrical storage systems have different power and energy ratings as shown in next figure [46]:

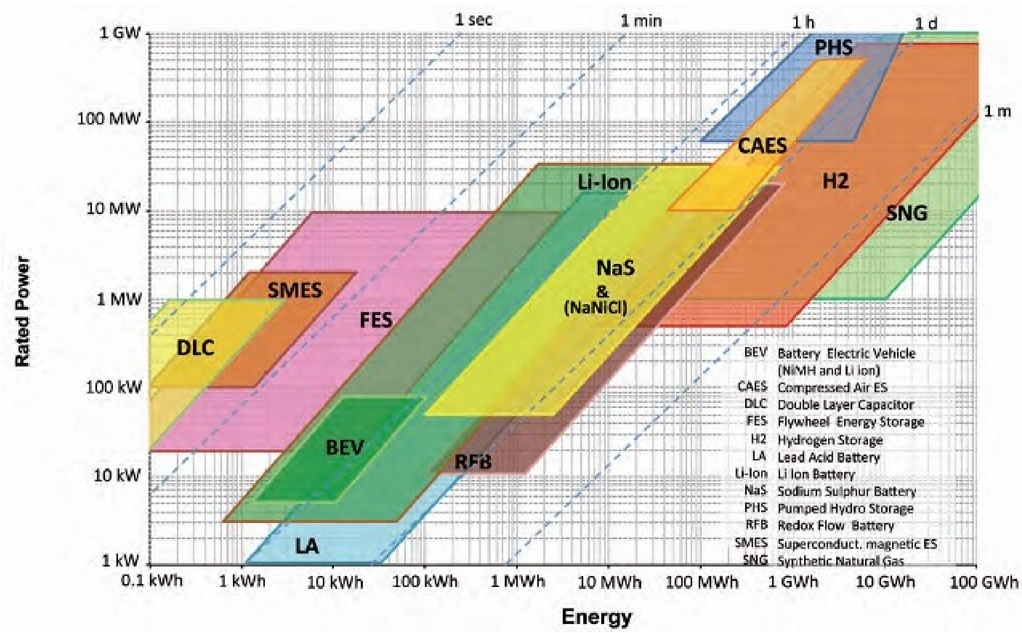


Figure 2-21 Rated Power vs Energy Capacity of ESS [46]

Here the focus is on batteries and hydrogen as the thesis's proposed system because they are highly scalable, portable, and dimensionally feasible for off-grid power system application. Two several types are used to enable the system to have a mid-term storage as batteries with quick response rate and hydrogen as a long-term storage system's reservoir in case no input power is being received from the renewable system to cover the house's power approximately for a designed period and in this thesis the period is designed to be a week. Another benefit for using hydrogen, hydrogen tanks can be added to increase the capacity without the need of expanding the fuel cells since tanks are separated from fuel cell power generation, unlike batteries which act as a storage and as power generators [47].

## 2.2.1 Battery Energy Storage

Batteries are interesting since they store huge amount of energy in the chemical bonds and release it when the chemical reaction takes a place. A battery is a device that consists of electrochemical cells which convert chemical energy into electrical one. The cell basically is formed from three parts as a positive electrode, a negative electrode, and liquid or solid electrolyte. A chemical reaction happens when the two electrodes are connected where electrons from negative terminal pass through to the positive terminal [47], [48], [49]. For the chemical reaction to be completed, proton, positive ion, passes through the electrolyte. The following figure illustrates the principle behind a galvanic battery cell [50]:

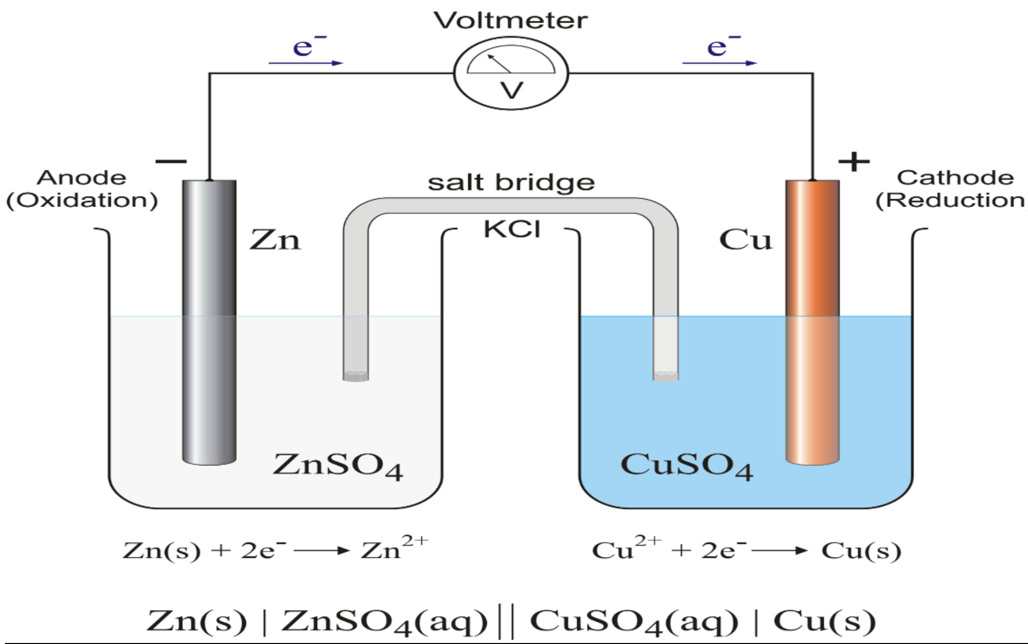


Figure 2-22 Galvanic Battery Cell [50]

Diverse types of batteries are produced to fit different applications requirements. They can be used for small application as a hand watch to a large-scale application as a smart grid battery storage system. There are basically two types of batteries as:

- Primary batteries which can be used for one time only.
- Secondary batteries which can be recharged once they are empty for multiple times or as called cycles.

Batteries can be connected in series, in parallel, or in a combination of both, to provide the required system's operating voltage and current. Batteries are different based on the chemical reaction and the elements involved in that reaction. Therefore, different elements and chemical reactions lead to different kind of batteries. The most common types of secondary batteries that can be used in off-grid systems are lead-acid, Nickel-cadmium, Nickel Metal Hydride and, lithium-ion. The following table compares the characteristics of those batteries [47], [51], [52]:

**Table 2-2 Comparison of battery types & Parameters**

| Parameters | Lead-Acid | Nickel Cadmium | Nickel Metal Hydride | Lithium-Ion |
|---|---|---|---|---|
| Nominal cell voltage (V) | 2.1 | 1.2 | 1.2 | 3.6 |
| Energy density (Wh/kg) | 30-40 | 40-60 | 30-80 | 150-250 |
| Specific power (W/kg) | 180 | 150 | 250-1000 | 1800 |
| Charge/discharge efficiency (%) | 70%-92% | 70%-90% | 66% | 99%+ |
| Self-discharge rate in (%/month) | 3%-4% | 20% | 30% | 5%-10% |
| Cycle durability3 (#) | 500-800 | 1500 | 500-1000 | 1200-10000 |

As seen from the table, Lithium-ion battery has better characteristics and more suitable for an off-grid system application. Those characteristics can be illustrated as:

- High energy density compares to other types of batteries which result in small storage space.

- High specific Power which is required for the off-grid system since it is the primary source of power after renewables.
- High Charge/Recharge efficiency so it is good for deep discharging.
- Lowest self-discharge rate over a moth that helps the battery remain charged for a prolonged period.
- A substantial number of cycles which extend the lifespan of such battery storage system.

These characteristics have made Lithium-ion battery to grow fast as in 2015, it became the most popular form of storage in the world by 85.6% of global energy storage system and a promising technology [53]. Thus, Lithium-ion battery model will be used in this thesis work. In the simulation, the model of the battery is designed and simulated in MATLAB SimPowerSystems™ Simulink and this battery model that is discussed in the paper [54] is chosen to be connected to the entire proposed system. The model represents distinct kinds of batteries and the user can choose which kind. The lithium-ion battery is chosen and is connected to an electric circuit to simulate charge/discharge modes.

Lithium-ion battery consists of Lithium Cobalt Oxide to form a positive electrode, Carbon to form a negative electrode and a very thin sheet of micro-punctured plastic to form a separator that passes only positive ions [52]. The battery is then modeled mathematically as described in the literature and fully discussed in this paper [55]. The equivalent battery model is shown in the following figure which basically has a voltage controlled source with serial resistor [52], [56]:

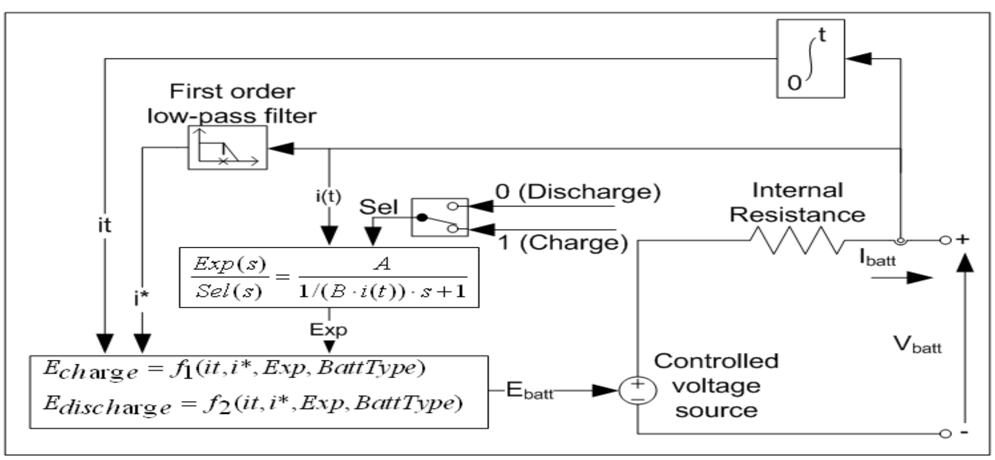


Figure 2-23 Battery Equivalent Model [52], [56]

The characteristic of charging lithium-ion battery regarding its current and voltage level are described in the following figure which helps in designing proper charge circuit to avoid over voltage and over current charging and keep the battery safe. On the other hand, when discharging Lithium-ion battery, the current shouldn't exceed the maximum discharging current which depends on the C rate (capacity rate) and cut-off discharging when low voltage level achieved, or the cell runs over temperature limits. In addition to both modes, a voltage balance circuit should be installed to monitor the voltage level of each individual cell and prevent voltage deviations among them.

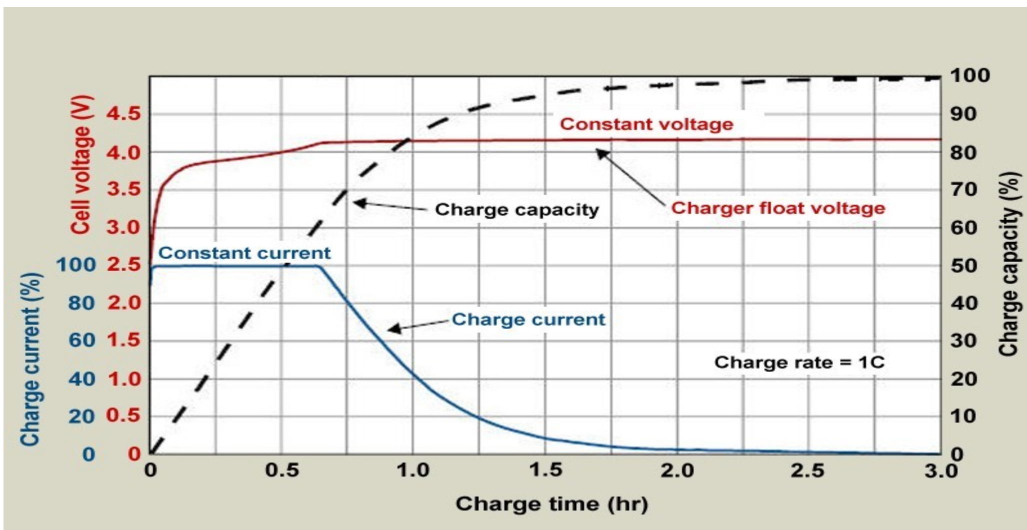


Figure 2-24 Lithium-ion Charging Characteristics [42]

The life of any battery is measured by battery life cycle which is the number of complete charge/discharge cycles that the battery can accomplish before its capacity falls under 80% of its original capacity [42].

### 2.2.2 Hydrogen Energy Storage

Hydrogen is the most abundant element in the universe of more than 90% of all atoms [57]. It is the simplest and smallest element with one proton and one electron. It is a gas at standard state conditions and is odorless, colorless, tasteless and nontoxic. Fusion of hydrogen atoms produces other elements as helium and a huge amount of energy. As an example, our main source of energy, sun, is fueled by hydrogen fusion for millions of years. On earth, hydrogen rarely found pure and is always chemically bonded. water is the most compound of hydrogen [57]. Hydrogen is mainly used in several chemical applications such as petrochemical cracking and in ammonia production.

Another use of hydrogen is in the energy field as an energy carrier. For example, aviation sector uses hydrogen to fuel space rockets on a large scale [57]. Many scientists study the idea of using hydrogen as an energy carrier as in their research such as Ohta in 1979, Nitsch and Voigt in 1988, Scoot and Hafele in 1990 and others [58]. Hydrogen is clean, sustainable and, abundant and when it burns it produces water and no GHG emissions give it a promising future as a fuel carrier. It can be generated using different chemical reactions such as Hydrogen can be produced by several industrial methods [42]:

- Steam reforming of natural gas.
- Chemical reduction of coal.
- Solar hydrogen using artificial photosynthesis.
- Partial oxidation of heavy oils.
- Water Thermal decomposition.
- Water Electrolysis.

However, in the application of generating hydrogen in an off-grid energy storage system, water electrolysis is the target since water can split into hydrogen and oxygen where hydrogen can be stored in tanks for later use. A typical Hydrogen storage system consists of Water electrolysis to produce hydrogen from surplus power, hydrogen storage tank to store the generated hydrogen for later use and a fuel cell system to reproduce electricity when needed by using the stored hydrogen.

**Water Electrolysis**

It is used to avoid inherited operation since this application aimed at the stand-alone off-grid system. Water electrolysis is an electrochemical process that converts water into hydrogen and oxygen with the help of electricity and requires additional temperature to complete the process. Thus, this process is an endothermal one. The overall reaction enthalpy requires 237 KJ/mole to produce two atoms of hydrogen and release one oxygen atom. The chemist Johann Wilhelm Ritter was the first scientist who used electrolysis of water to generate hydrogen as early as 1800 [57].

Usually, the oxygen is vented to the atmosphere for economical purpose and to keep system size small as possible. Water Electrolysis has many types as alkaline, acidic and, high-temperature steam electrolysis where at 1700 °C water decomposes forming hydrogen but here the focus will be on Alkaline Electrolysis since it is the most dominating one and uses the surplus generated electricity for the project [58]. The electrolysis cell requires minimum 1.23 V and 2 Faraday of electrons to start working and generate hydrogen. Adding heat to the cell lower the voltage needed [42]. Many cells are stacked to form an alkaline electrolyzer. There are two categories of Alkaline electrolyzer as conventional and advanced [58].

The conventional one uses potassium hydroxide with a concentration of 20-30% by weight since water is poorly conduct electricity, acid or alkaline must be added to let the reaction occur. The preference of choosing potassium hydroxide is because of optimal conductivity and corrosion resistance. The electrolyzer operates at 1 to 30 bar pressure with 70 to 100 °C temperature [58]. The total hydrogen generated is then either stored at normal pressure or pressurized to a certain level of pressure to have higher fuel density. Here is a figure describing the design of Alkaline electrolysis cell and show the difference between monopolar and bipolar one:

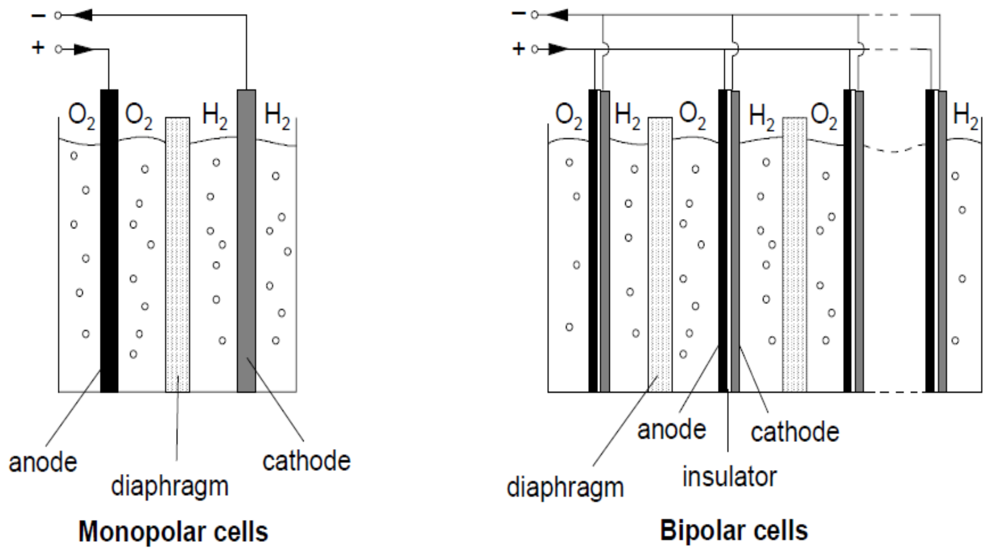


Figure 2-25 Alkaline electrolysis Cell [58]

**Hydrogen Storage**

The second step after generating hydrogen is to store it. Since hydrogen is a very light gas with a low density of 0.08245 $Kg/m^3$ at standard state conditions, it must be compressed under high pressure or liquefied at a very low temperature or chemically bonded to metal hydrides or to super activated carbon [57], [58]. However, for off-grid application the first two methods can be used and compress hydrogen is the most popular choice for the small amount of storage. For larger quantity of hydrogen, underground piping systems or salt caverns with several 100,000 $m^3$ volumes are used [58].

**Hydrogen Fuel cell**

Hydrogen fuel cell is considered the promising technology because it has a feature of converting chemical energy directly into electrical energy. It is like batteries but require fuel from an external source such as from hydrogen tank and will keep generating electricity as long as fuel is available. There is no clear idea of who first invented the fuel cell. The chemist Christian Friedrich conducted an experiment in 1838 and the English William Grove discovered the basic operating principle of a fuel cell in 1839 by reversing the process of water electrolysis to generate electricity from hydrogen and oxygen and invented the fuel cell that almost has the same principle till now [57], [58], [59]. By 1963, NASA has developed hydrogen fuel cells to supply power for satellites and space capsules. In addition, the U.S nave uses them for submarines [59]. To generate electricity, a pure hydrogen gas or a fuel containing hydrocarbon flow into the anode (negative electrode) and oxygen from the air or any oxidation compound is fed to the cathode (positive electrode). The two electrodes are separated by electrolyte where it allows protons to pass through and the waste of this reaction is water [57]. Heat is released as the by-product. The figure shows the operation of the reaction and the cell components:

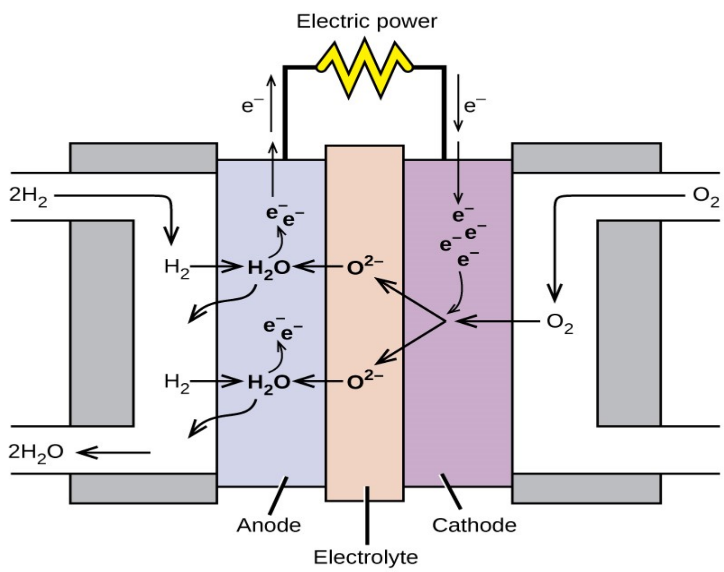


Figure 2-26 Generic Fuel Cell (Preface by *Rice University* CC)

A fuel cell operates quietly and efficiently and consumes hydrogen as a fuel to produce electricity, water, and heat and does not need recharging. Thus, the waste of water is considered a zero-emission and eco-friendly power generation [59]. There are several types of fuel cells based on the electrolyte membrane type. Each type has distinct characteristics of temperature operational range and cell efficiency. The following table explains more [52], [57], [58]:

**Table 2-3 Several Types of Fuel Cell**

| Type | Fuel Gas | Electrolyte | Operating temperature | Oxida nt | Cell Efficiency |
|---|---|---|---|---|---|
| Solid oxide fuel cell (SOFC) | Hydrocarbons or biogas or hydrogen | Ceramic YSZ | 800-1000 °C | Oxyge n or air | 60-65% |
| Molten carbonate fuel cell (MCFC) | Hydrocarbons or biogas or hydrogen | Alkali carbonate melt | 600-650 °C | Oxyge n or air | 65% |
| Phosphoric acid fuel cell (PAFC) | Hydrogen | Phosphoric acid | 160-220 °C | Oxyge n or air | 55% |
| Direct methanol fuel cell (DMFC) | Methanol | Proton conductive membrane | 60-130 °C | Oxyge n or air | 20-30% |
| Proton exchange membrane fuel cell | Hydrogen | Proton conductive polymer membrane | 60-120 °C | Oxyge n or air | 40-60% |

| | | | | | |
|---|---|---|---|---|---|
| (PEMFC) | | | | | |
| Alkaline fuel cell<br><br>(AFC) | Hydrogen | Potash lye | 20-90 °C | Oxyge n | 60-70% |

The most frequent fuel cell type used is the proton-electron membrane (PEM) due to its low operating temperature which is suitable for residential applications, high efficiency between 40 to 60 % and fast start-up [52]. The PEM cell consists of two electrodes separated by a proton conducting polymer membrane. The negative electrode is supplied by hydrogen gas while air or oxygen flows in the positive electrode. Electrons flow from negative electrode to the positive one through an electric load generating differential voltage. The hydrogen proton simultaneously passes through the membrane and react with oxygen to form water and some heat is generated. A platinum catalyst is used to support the split of hydrogen into a positive ion and an electron [57], [60].

More advances in designing fuel cells have been achieved in latest years, and more companies getting involved in making them commercially available. However, the market cap s still low compared to batteries due to the high price of the fuel cell and hydrogen system requires many components to operate fully [57].

## 2.3 Hybrid Power Systems

An electric power system is a network of electrical components designed to supply, transfer, store, and use electricity. The national power grid is a major example representing the electric power system where it consists of three major parts as power generation stations to generate power, transmission systems that transfer power from the supply side to load and distribution system which conditions power and then feeds it to homes and end-user consumers. The first grid designed on a large scale was in New York in 1882 by the inventor Thomas Edison and his company, The Edison Electric Light Company. The grid was developed initially to power around 3000 lamps for 59 customers using steam-powered electric generator [61].

Since then, the conventional grid was designed to work in a vertical structure as generation, transmission and distribution with the help of power controllers, power protection system and SCADA system for overall grid monitoring, to maintain reliability, stability, and efficiency. However, this design is facing challenges in today's power market such as power losses in transmission which are typically from 7% to 12% and other challenges [62]. To overcome those challenges, the idea of the smart grid is introduced, approved and considered as the new development of the existing utility grid [10]. The basic idea behind smart grid is to enhance communication between different component of the system, make two-way power flow and, add real-time measurement instruments. As a result, the grid will work with optimal power generation based on high information quality monitoring and forecasting and also the grid will be protected against threats from internal system failures or external threats [10].

### 2.3.1 Smart Power Grid

The smart grid includes variety of new equipment and systems including smart meters, smart appliances, renewable energy power systems and maybe other more in the future. Therefore, having power converters and power control of the distributed power generation and usage is a main stone of the smart grid in addition to a high-quality two-way communication system. Smart grid policy is organized in Europe under Smart Grid European Technology Platform and it is described in the U.S under 17381 law code [63], [64].

According to Smart Grid book by James Momoh [10], the smart grid will be capable of:

- Manipulating uncertainties in schedules and power transfers across the network.
- Cooperating with renewable power either from customers of micro-grids.
- Optimizing the quality and reliability of transferring power and meeting demand.
- Managing and dealing with unpredictable events and uncertainties in any operations and planning for better forecasting.

Here is a figure of a possible scenario of a power system based on smart grid technology discussed and introduced by Marco Liserre, Thilo Sauter, and John Y. Hung in their article "Future Energy Systems" in 2010 [65].

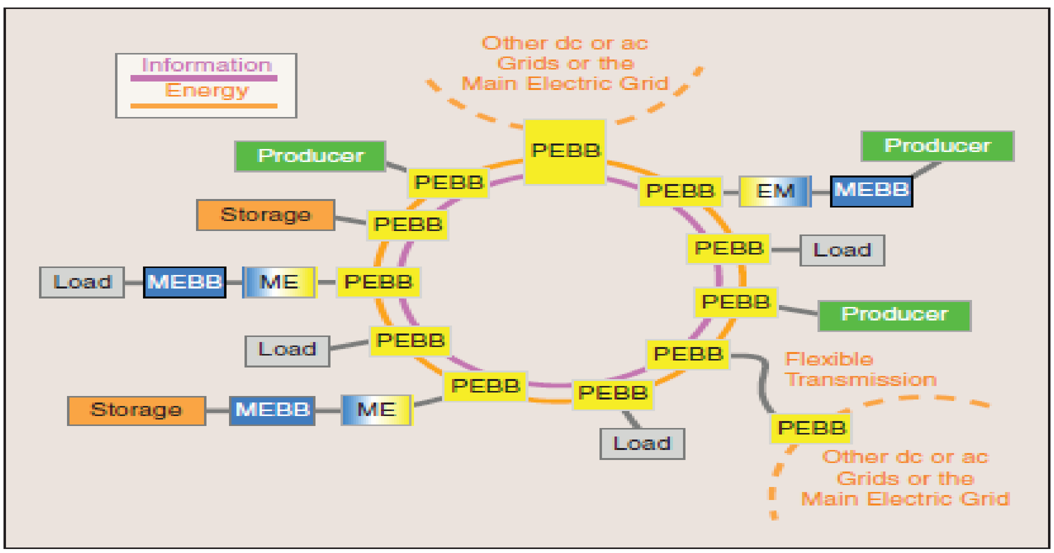


Figure 2-27 possible scenario of a power system based on smart grid technology [65]

As shown in the figure, the smart grid consists of two circles the outer one that represents power flow while the inner one represents data flow over communication channels. Different parties are joining the network as producers, energy storage, and consumers. The main block of controlling, transforming and converting the power flow between different parties is power electronics and the way of controlling such a network is discussed in different papers as [66], [67]. Power electronics are a key role in handling power flow between parties and will be discussed later in this section.

So to conclude, a smart grid design enables the power industry to observe and control parts of the power system at higher resolution in time and space. Also, another purpose of this design is to perform a real-time information exchange to optimize operations as efficient as possible. Smart grid design would manage any part of the grid anytime from high-frequency switching in microsecond to solar and wind output variations in minutes. It would diminish the future effects of the carbon emissions generated by power production on a decade scale [65].

### 2.3.2 Stand-Alone Power System

On the other side, there are smaller power systems to support designated purposes. Those systems can be connected to the grid or can work independently where in this case it is called stand-alone power system. Those systems can be found in hospitals, industry, commercial malls and remote site homes and communities. Some of them are used for emergency situations such as uninterruptible power supply, UPS. Those stand-alone systems are divided into two main categories as grid-tie and off-grid power system. The grid tie system has a feature of being connected to the main grid so when extra power is required and the system isn't capable, the system draws power from the grid and when extra power is generated, the system can sell that power to the grid. The second type is the off-grid system which is totally independent of the grid and is designed mainly to support homes, industries and remote-area communities that is technically difficult to be connected to the grid or the grid power transmission is costly and not economically feasible.

Stand-alone systems are consisting of mainly one power source, a power converter, and a power consumer. However, in order to achieve higher power quality and total power system reliability and stability, other components are to be added to the system as multiple power sources, energy storage units, and overall power flow controller. Such a system is called; hybrid off-grid system. A hybrid off-grid system is a collection of at least two power sources with at least one energy storage to supply a load without being connected to any grid and has power converters that enable the power flow between those components under the supervision and management of a power flow controller [58]. The power sources vary based on the application, location and the purpose of system use but here in this thesis, the concentration is on the hybrid renewable off-grid system is the main topic so next section will elaborate and discuss more about it.

### 2.3.3 Renewable Hybrid Off-Grid Power System

The hybrid renewable off-grid system is usually popular as a hybrid renewable energy system, HRES [68] and [69], and is designed to harvest renewable energy and use that energy independently and efficiently to supply a specific load such as a house, neighborhood or a village or even a larger scale. The system uses energy storage units to balance the supply-demand, support power quality, and enhance system reliability and ability to work alone. Storage is mainly implemented as a battery bank, but other solutions exist including fuel cells and etc. [70]. Most system designers aim to use dissimilar renewable sources, unlike energy storage to overcome constraints and limits of each component. In contrast, the load behavior is really an important factor in designing such a HRES and usually is divided into four categories as baseload, intermediate, peaking, intermittent or unschedulable [62]. Baseload is referring to the load that does not vary during the day. The intermediate is the load that varies no more than twice a day. The peaking load is when the load reaches its maximum in a day. The intermittent or unschedulable load happens immediately without further planning [42]. The load generated at home is basically a result of operating several home appliances and there are charts that illustrate their power usage and their total energy consumption over a month period. An interesting home appliances chart is designed by TorontHydro® and can be found at their website [71].Renewable energy resources and the selection of solar and wind over others are well discussed in section 2.1 of this chapter while energy storage system and the selection of battery and fuel cell are discussed in section 2.2. However, the remaining components of HRES will be discussed in section 2.3.

- **System configuration and links**

  There are several configurations to link renewable power supplies with multiple energy storage units to supply an AC and DC loads [72], [73]. Three main configurations that cover most of the available ones would be described as:

1. Electricity generation coupled to DC bus line:

   Renewable power sources and energy storage units are connected to a main DC bus line. AC power component as wind turbine needs an AC/DC converter. The solar PV might need a DC/DC converter. The battery is controlled and protected from overcharge and discharge by a battery management system, then it supplies power to the DC loads in response to the demand. Hydrogen system is also connect using a DC/DC converter. DC loads can be directly connected to the main DC line and AC loads can be supplied by a DC/AC inverter.

2. Electricity generation coupled to AC bus line:

   Renewable power sources and energy storage units are connected to a main AC bus line. AC generating components such as wind turbine may be directly connected to the AC bus line or may need an AC/AC converter for stable coupling. The solar PV needs a DC/AC inverter. The battery is controlled and protected from overcharge and discharge by a battery management system, then it supplies power to a bi-directional master inverter. Hydrogen system is also connect using a bi-directional master inverter. AC loads can be directly connected to the main AC line and DC loads can be supplied by an AC/DC converter.

3. Electricity generation coupled at AC/DC bus line:

   DC generating sources and DC energy storage units are connected to the main DC line while AC generating sources and AC energy storage units are connected to the main AC line. Both lines are connected using a master bidirectional inverter which supplies AC loads and DC loads can be supplied by an AC/DC converter.

In this thesis work, DC bus line configuration is used and the following figure illustrates general DC bus line as mentioned in [73]:

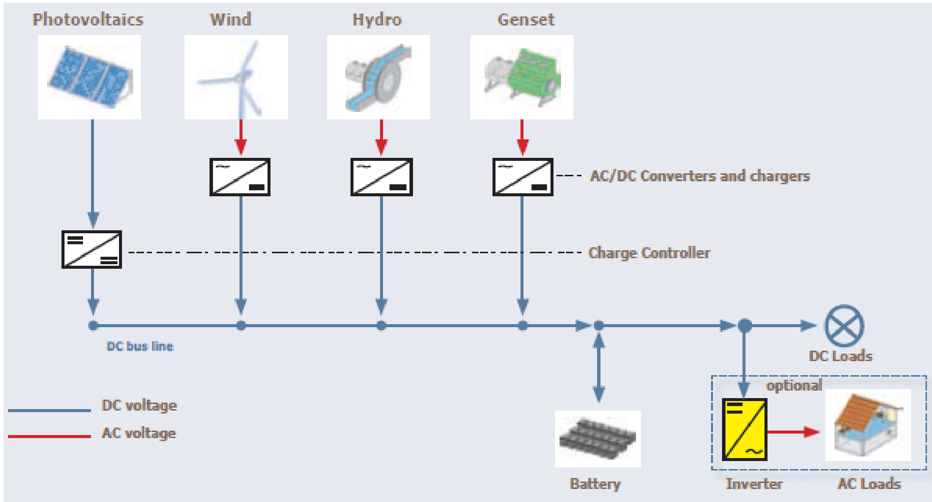


Figure 2-28 Electricity Generation using DC Bus Line [73]

### 2.3.4 Power Electronics

A power converter is an electronic circuit made of different passive and active electronic components to perform power conversion. Power converts consist of mainly two stages as a power stage and a control stage [52]. In the power stage, the power is transferred from one system to another while the control stage controls this amount of power by controlling the voltage and current values. Power converters are divided into four categories based on their usage to:

- DC-AC power rectifier.
- AC-DC power inverter.
- DC-DC power converter.
- AC-AC power converter with same or different frequencies.

The use of power converter generally is to condition, maximize and match the power between two circuits. A DC-AC power rectifier is used to change the current from AC to DC to suit the DC followed circuit. Whereas DC-AC inverter is converting DC current to feed an AC circuit. The DC-DC and the AC-AC power converts are designed to change the voltage or the current between two circuits or frequencies as in AC-AC converter. The following figure collected all types together:

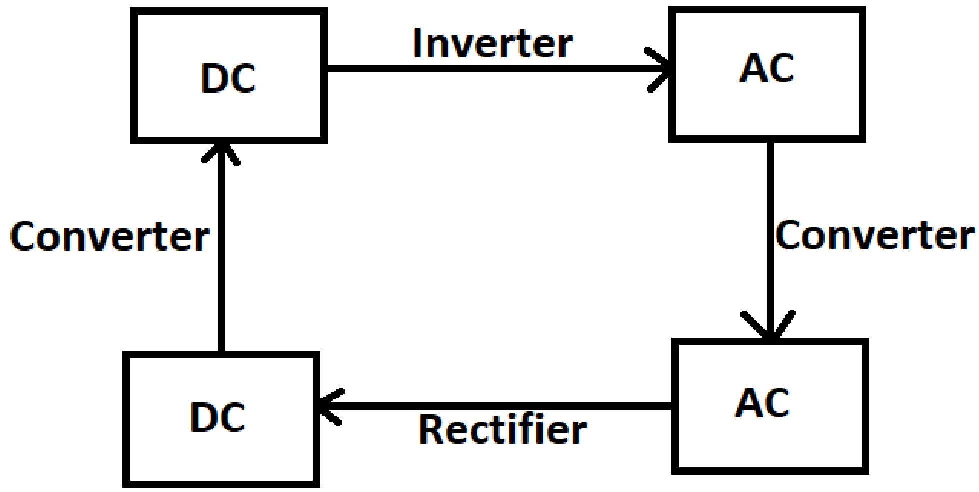


Figure 2-29 Power Converter Types

Power converters are the heart of hybrid power system since they are used for numerous purposes such as controlling the power flow or extracting maximum power by changing the circuit resistance as in MPPT power extraction (to ensure maximum power extraction) or could be used to adjust the output voltage with variable load to keep the system rigid and reliant (to enhance power quality).

In power electronics, the passive components in the circuit are inductors, capacitors, and resistors while the active ones are switching transistors. In addition to a circuit that controls the switching frequency of that transistor. The DC-DC circuit, for example, can either by a boost or a buck converter or both. A boost converter has an output voltage higher than the input voltage and the buck converter is a step-down that reduces the input voltage. Both converters have D value that can be controlled by an external control circuit. The switch duty ratio, D, determine the relationship between input and output voltages. The switch duty ratio ranges from 0 to 1 [74].

Control of power flow can be achieved by controlling the switching duty ratio of each power converter and off/on control of power protection circuits. More definitions and details about power converters and their operation and design can be found in this book [74] as well as this article [75].

Protective circuits are used to prevent injury or system damage during failures. The most common type is fuse which shut off the current when exceeds a certain threshold. Also, there is mechanical and electrical protective circuit which has a control input and can be monitored by the main controller. Those elements are highly recommended in hybrid energy system design to have overall control of various parts of the system [76], [77].

### 2.3.5 Power Flow Control

HRES insistent a more complex control mechanism comparing to a single-supply power system. System's optimal performance requires an advance and higher supervisory controller that looks for several combined components and harmonizes them [78]. Specifically, the power exchange among solar PV, wind turbine, battery, water electrolyzer, fuel cell and the load must be firmly regulated in order to guarantee that the energy captured is delivered and stored as much as possible. Although there are several system components, as a fuel cell, which independently controlled, they must be globally managed in order to operate the system effectively and in an integrated manner. The supervisory controller ensures renewable sources maximum power and smooth power flow in the main bus and bus voltage stability.

The supervisory controller takes input data from solar PV, wind turbine, battery system, hydrogen tank and load at a specific sampling rate. Based on these data, the supervisory controller commands each individual component's controller for a certain action to feed the load without intermits or lower output power quality. Also, the supervisory controller is responsible to control the battery in certain limitations to avoid stressing and shorting its lifespan and avoid running out of storage. It also takes operation decisions based on the designed rules and strategies [79]. It assists load/supply and adjusts the storage systems accordingly. More objectives can be added to the supervisory design requirements list.

# 3. Materials and Methods

## 3.1 Data Collection

Data is a fundamental element and essential part of designing, modeling and simulating a power system. To start with any power system design, the designer must first know how much power is required by the consumer and how the consumer demand behavior changes over the day as well as over the seasons. Furthermore, in a power system that is relying on harvesting renewables as HRES, weather data collection is a key in the process of understanding how much renewable energy is available at that site, and determine the size of solar PV, wind turbine as well as energy storage systems. A while back, weather databases were designed and structured to collect weather data such as solar direct and global radiation, wind speed and direction, ambient temperature, rain perception, and relative humidity at an hourly basis rate to picture the weather map of a certain area.

The most common database of describing certain climate is called TMY, a typical metrological year which, presents a range of weather phenomena for the location in search, while still giving annual averages that are consistent with the long-term averages for that certain location. For global data collection, NASA has recorded weather data and provide them to the public in their website under NASA Surface meteorology and Solar Energy: Global Data Sets and also develops a specific webpage for solar renewable energy [80]. Since 1983, they started collecting various weather data worldwide and manipulating average monthly and annual values. Based on this database, researchers can have an idea about any location climate worldwide and use the data for designing, modeling and simulating their proposed systems. Moreover, the NREL established a national solar radiation database for the U.S. plus Guam and Puerto Rico for solar research purpose. They created three different databases successively one after another and the latest database has a data resolution of 30 minutes [81]. Canada also, Created a weather database of various location all over Canada for the period between 1998 and 2014 [82]. Also, one of the thought-provoking website to easily visualize and download solar data from is a website designed by Gatton Solar Research Facility at the University of Queensland in Australia. This website provides life and a very high data resolution of one-minute solar data. This interesting data can be found on the Gatton Solar Research Facility website [83].

Whereas, wind data is hard to find in regular databases since most databases concentrate more on solar and wind speed collected for weather forecasting which does not state the elevation of that wind speed. The left choice is either to take NASA data or to take data provided by local weather casting. Wind data is collected directly from a weather station installed close to a project of smart meters installed in three houses in Alberta province and the weather station support wind data with a resolution of three minutes which more realistic for wind turbine dataset compared to weather wind speed without specified elevation. On the other hand, the smart meters provide solar power and house demand data over the year 2016 with a resolution of 15 minutes.

Therefore, the designed model utilizes real solar power data and house demand data from the smart meters with 15-minute resolution, while real wind power data are collected from a nearby weather station with a modified 15-minute resolution to match other data. This data collection is considered to achieve more realistic simulation results.

There is another method to generating weather data using a mathematical model instead of collecting real data. Scientists and researchers designed several mathematical models for wind speed in general and based on that model wind power can be derived. For example, the generic broadband model of Van der Hoven [84] provides information on the power density of wind speed for a specific temperature area zone. Other Scientists and researchers designed several solar models that describe the solar irradiance over a day of different seasons. A solar PV model uses this solar irradiance data to produce an estimate solar power data with a certain solar PV efficiency. This method is used in a research article of intelligent control of distributed energy generation [85].

## 3.2 System Sizing

Unit sizing is essential for assuring lowest system cost with highest system power reliability. Optimal unit sizing maintains the balance between reliable system operation while reducing the net present system cost. Oversizing the system units will increase total system cost while under sizing may lead to power failure and blackout. Therefore, there are two main principal factors to unit sizing as [48]:

- Economic factor
- Power reliability factor

And researchers have designed parameters, tools, and methodologies to evaluate those factors. For economic factor, several parameters are existed to evaluate the system from the economic point of view and here five tools are to be discussed.

First, levelized cost of energy, LCE, which is the evaluation of energy production including periodic and nonperiodic costs over the system lifetime. It is calculated as the ratio of the total annualized cost of the system, ACS, to the annual electricity production as:

$$LCE = \frac{ACS}{Total\ Electrcity} \tag{3-1}$$

Second, annualized cost of the system, ACS, that represents the total annual capital, replacement and operation and maintenance costs. It is formed as:

$$ACS = Captial\ Cost + Replacement\ Cost + Maintenance\ Cost \tag{3-2}$$

Third, net present cost, NPC, which represents the life cycle cost of the HRES. It shows the system's cash flow with discounted back to the present method. It is a collection of capital, maintenance, replacement, and components slave costs calculated to the present value. The NPC can be calculated using the following equation:

$$NPC = \frac{Total\ annual\ cost}{Capital\ recover\ factor} \tag{3-3}$$

Fourth, internal rate of return, IRR, which is the true investment interest of the system during its lifetime. It has several names as return on investment and time-adjusted rate of return.

Finally, payback period, PBP, is the time length of the investment to recover the initial capital cost of the system.

For power reliability factor, three functions are discussed in this section as:

1. Loss of power supply probability: it represents the ratio of loss of power supply to load demand at a given time.
2. Expected energy not supplied (EENS): it is the expected energy not supplied to the load when the load is greater than power generation. This quantity is illustrated by the following equation as:

   $$EENS = \sum_{k=1}^{8760} L * D \tag{3-4}$$

   Where L is the average annual demand and D is the period where demand is not met.

3. Level of autonomy: it is the period percentage of which load is met. It can be calculated as the inverse of the duration of loss of load to the total operation duration as:

   $$\text{Level of autonomy} = 1 - \frac{Duration\ of\ loss\ of\ load}{Total\ operation\ duration} \tag{3-5}$$

The next step of unit sizing is determining the methodology of evaluating and optimizing the previous tools and functions. Researchers focus on different optimization objectives and methodology based on their system and operation requirements for their systems. Multiple methodologies have been in literature and here some are to be discussed as the following:

1) Artificial intelligence approach: number of approaches have been reported as genetic algorithms, artificial neural networks, particle swarm optimization, harmony search, ant colony optimization and other. This approach can handle the nonlinearity of the system and most of them don't require weather data availability to sizing system components [48]. For example, Hongxing Yang designed power reliability model based on loss of power supply probability plus an economic model based on annualized system cost using genetic algorithms approach [86].
2) Multi-objective approach: where optimization tools are used to solve the optimization problem for more than one objective.
3) Iterative approach: where optimal performance for the hybrid renewable energy system is achieved using a program that recurs till the final solution is optimum. In this approach, usually, net present cost, NPC, or levelized cost of energy, LCE, tools are used to optimize the system cost whereas loss of power supply probability, LPSP, the function is used to achieve power reliability.
4) Analytical approach: where a computational model is used to find system feasibility by characterizing each component of the system. Then, several system configurations are evaluated by comparing single or multiple performance indexes and the best fit is the optimum sizing.
5) Probabilistic approach: this approach studies the changes in power resources or demand and then a risk model can be derived. However, this approach does not recognize the change in the dynamic of the system performance.
6) Graphical construction approach: it is one of the linear optimization tools that works only for two decision variables.
7) Commercially available computer tools: they are the most common tools for evaluating the system performance and analyze its cost and power reliability. Energy production cost of different system configurations can be easily visualized using these tools to find the optimum configuration for best performance. Several tools are available for designing of hybrid renewable energy systems, such as HOMER, HYBRID2, and HOGA.

We intend to size each component based on certain factors. The main factors to focus on are the maximum power supply and the balance between consumer demand and renewable energy generation over a year. These factors are part power reliability factor discussed above and certain tools such as loos of power supply probability can be part of this sizing method.

## 3.3 System designing approaches

There has been a number of studies examining the role of energy storage systems (ESS) such as batteries and fuel cells (FC) in hybrid renewable energy system (HRES) [87] [88] [89] [90] [91]. According to [87], due to their fast ramping capability, fuel cell systems can mitigate the problems related to the intermittent power generation of DGs. This phenomenon is observed in [88] where a computer model for simulating a transient operation of a tubular solid oxide fuel cell was proposed. A nonlinear mathematical model of an internally reforming molten carbonate fuel cell plant was proposed in [89] to evaluate the cell responses to varying load demands and to define transient limitations and control requirements. A fuzzy logic based supervisory controller was proposed in [90] with FC providing power to the load and ultracapacitors (UCs) assisting during transients. However, the combination of FC and UC is not economically feasible.

As the objective of this work is not focused on transients, the use of expensive UCs should be avoided. An important advantage of a large UC is a high rate of discharge required to provide a fast response of the FC. Hence, other technologies must be used to obtain more desirable results. The issue of the slow response of batteries can be overcome by taking advantage of the fast response characteristics of fuel cells [87] for damping out oscillations caused by a frequent change in load and generation within a smart grid.

A comprehensive review of various methods [91] pointed out that there are still issues that need to be addressed, mainly related to failures affecting end consumers. Additional work on storage and FC and storage can be found in [92], where an electrical equivalent circuit of a fuel cell generation system for control purpose based on the fuzzy logic controller (FLC) was developed and proposed. According to [87], several tests were carried out on the phosphoric acid fuel cell plant installed in Germany. The reported results mainly focused on the response time for load change from 25% of the rated power to full load. Although all cited studies achieve good results for their specific purposes, they did not consider the control of HRES power flows using a fuzzy logic controller aimed to use the excess power to generate hydrogen from water. This would not only improve the stability of the overall system but also efficiently manage the energy storage elements, prolonging the life of the entire storage system while adequately supplying the demand side.

In this contribution, a novel fuzzy logic controller for HRES with multiple types of storage is described. The proposed scheme solves issues related to the needs of consumers pointed out in [91]. The solution focuses on the satisfactory supply of the demand side while ensuring the safety of lithium-ion battery and maintaining its efficiency and reliability. A comprehensive evaluation of the proposed scheme and validation of its effectiveness is conducted using MATLAB SimPowerSystems™ using real solar power, wind, and load data.

While there is a specific controller for each component of the system, there must be a global controller to manage the HRES system operation and power flow between its components towards the designated objective and in an integrated manner. This global controller should organize the power flow interaction in the power bus-line and assure good power quality delivery to the load while monitoring the level of energy stored in energy storage units [79].

## 3.4 Our system modeling

In this section, various subsystems of the proposed design are described and discussed. Each subsystem is modeled individually in Matlab Simulink. Power electronics converters, which are the coupling components for the power flow, are not discussed in this section since they are considered as 100% efficiency ’ideal’ power converters in this work.

### 3.4.1 System Dynamics

The system used in this study is a simplified model of a smart power system with wind and solar powers. The configuration of the system used is shown in the following figure. The solar source generates most of its power during the daytime is used to cover the day high demand due to high electricity usage for air conditioning and to support daily activities.

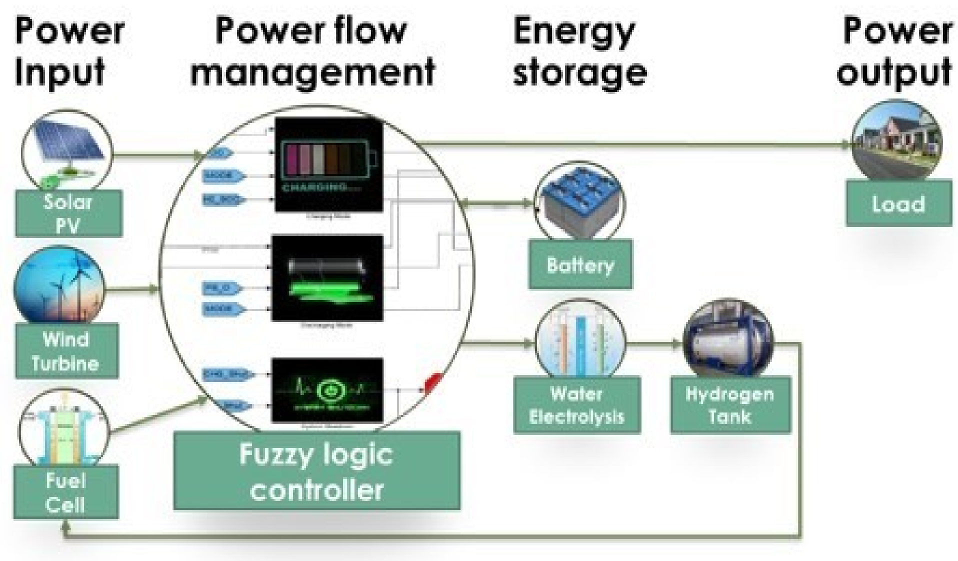


Figure 3-1 The Studied Smart Power System

On the other hand, availability of wind power, WP is spread over the day with more power seen at night. Therefore, the combination of the two sources provides enough total power to supply the load. In addition, the system has two energy storage elements: a battery bank and a full hydrogen system that can generate hydrogen from water using excess power and generate electricity from hydrogen using hydrogen FC when required.

The main supervisory controller directs the flows of power to the load and to and from the energy storage elements using two operating modes. In the charging mode, the FLC assigns a percentage of the excess power to the battery and the remaining power to water electrolysis, based on three inputs to the FLC. Similarly, in the discharging mode, the FLC assigns a percentage of required power from the battery and from the hydrogen fuel cells based on three inputs to the FLC. Since the system relies only on energy storage elements to handle surplus and required power (i.e. it is not connected to the grid); it is called off-grid hybrid renewable energy system [93], [94], [95]. All links between subsystems are DC links and power is converted to AC before supplying the load via DC-AC inverter with assumed ideal efficiency.

### 3.4.2 Solar Photovoltaic Subsystem

In this thesis, it is assumed that maximum power point tracker (MPPT) is used to extract maximum possible power from PV, and a DC-DC power converter is used to match the MPPT output voltage with the system voltage. The PV cells are operating based on photoelectric effect [21]. PV cells convert light with different wavelengths into a current at their PN junction, producing electricity directly from the cells when connected to a load. According to [25] the current produced is given by

$$I_{total} = I_0(e^{qV/kT} - 1) - I_L \tag{3-6}$$

where $k$ is Boltzmann's constant, $I_0$ sets the current scale and $q$ is the electric charge of the particles which comprise the current $I_{total}$. Also, $I_L$ is the light generated current, and $T$ is the ambient temperature. Based on the solar irradiance and the ambient temperature, which are two crucial physical quantities in PV technology, the PV cell corresponds to and produce open circuit voltage and closed circuit current [25]. Thereafter, the PV cells are connected to a MPPT which is connected to a DC-DC power converter and finally to the system's DC bus. For simulation purposes, real solar power data is collected from an installed PV panels on the roof of a house which provides solar data to the smart meter. Then, this data is provided to Matlab Simulink model through Matlab m-file.

### 3.4.3 Wind Turbine Subsystem

A wind turbine converts the kinetic energy of air in terms of air velocity into electric power using an electrical generator. Wind power is a result of air speed, air density and rotor area [96]. The mechanical power extracted by the rotor, which drives the electrical generator, can be calculated according to:

$$P_{eff} = C_p \eta_{gear} \eta_{gen} \eta_{ele} P_w = \frac{1}{2} (\eta_t \rho A \bar{u}^3) \quad (3\text{-}7)$$

where $P_{eff}$ is the percentage of the rated output, $P_w$ is the mechanical power in the moving air, $\rho$ is the air density, $A$ $is$ the area swept by the rotor blades, and $u$ is the velocity of the air.

This power is applied to the rotor of the electric generator to produce electricity. WP is only generated after certain cut-in airspeed. It then increases the airspeed until reaching a rated steady value, and remains steady until the wind turbine reaches the cut-off speed [96]. The wind turbine is assumed to work at the maximum power point. Thereafter, it is connected to MPPT, AC-DC power converter, and finally to the system. For simulation purposes, Wind power data from a location in Alberta is supplied to the Matlab Simulink model for best simulation result.

### 3.4.4 Battery Subsystem

In this work, batteries are used as the primary energy storage system for short to medium storage term. This subsystem is based on the generic battery block provided by Simscape Power Systems in Simulink environment [54]. The battery type is chosen as a rechargeable lithium-ion battery of 5 kWh capacity with 2C charging and discharging power limits. Detailed model of the battery system, including the equivalent circuit for both the charging and discharging modes, can be found in [54]. The battery is connected to the system using a bidirectional DC-DC converter with ideal efficiency and behavior and is controlled by a battery management system that receives control signals from the main controller. This figure shows the designed battery subsystem:

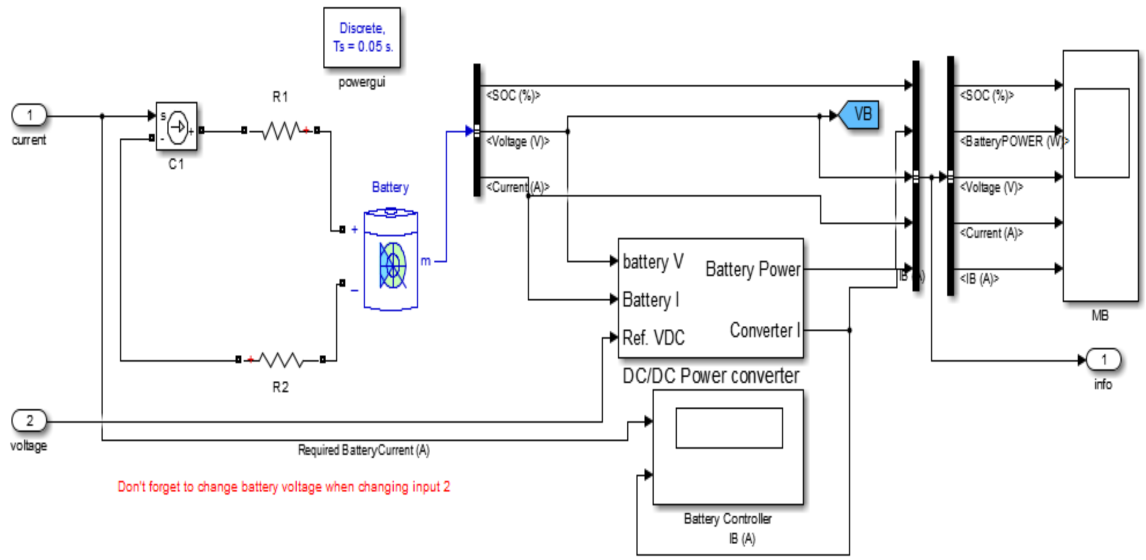


Figure 3-2 Battery subsystem Scheme

### 3.4.5 Hydrogen Subsystem

Hydrogen fuel represents the long-term storage for storing extra energy in big quantities for days and supports battery subsystem when a large load is applied in preventing battery damage, battery working insufficiently or shorten its lifespan. Ignoring hydrogen Compressor and other auxiliary components, this work considers a hydrogen subsystem consisting of three major blocks, namely hydrogen generation, hydrogen storage, and hydrogen fuel cells.

In charging mode, hydrogen is generated by the surplus power that fuzzy controller distributes. That power supplies a water electrolysis which then generates hydrogen. The moles of hydrogen generated is given by the following chemical equation [70]:

$$2H_2O + electrical\ energy \rightarrow 2H_2 + O_2 \qquad (3\text{-}8)$$

The model of water electrolysis in this project is based on a model mentioned in [70] and is expressed mathematically as :

$$\eta H2 = \frac{\eta F * \eta C * ie}{2F} \qquad (3\text{-}9)$$

where $\eta_{H2}$ is the rate of produced hydrogen, $\eta_F$ is Faraday efficiency, $F$ is Faraday Constant, $\eta_C$ is the number of electrolysis cells and that is the electric current in the cell. The following figure shows the design of the proposed water electrolysis subsystem.:

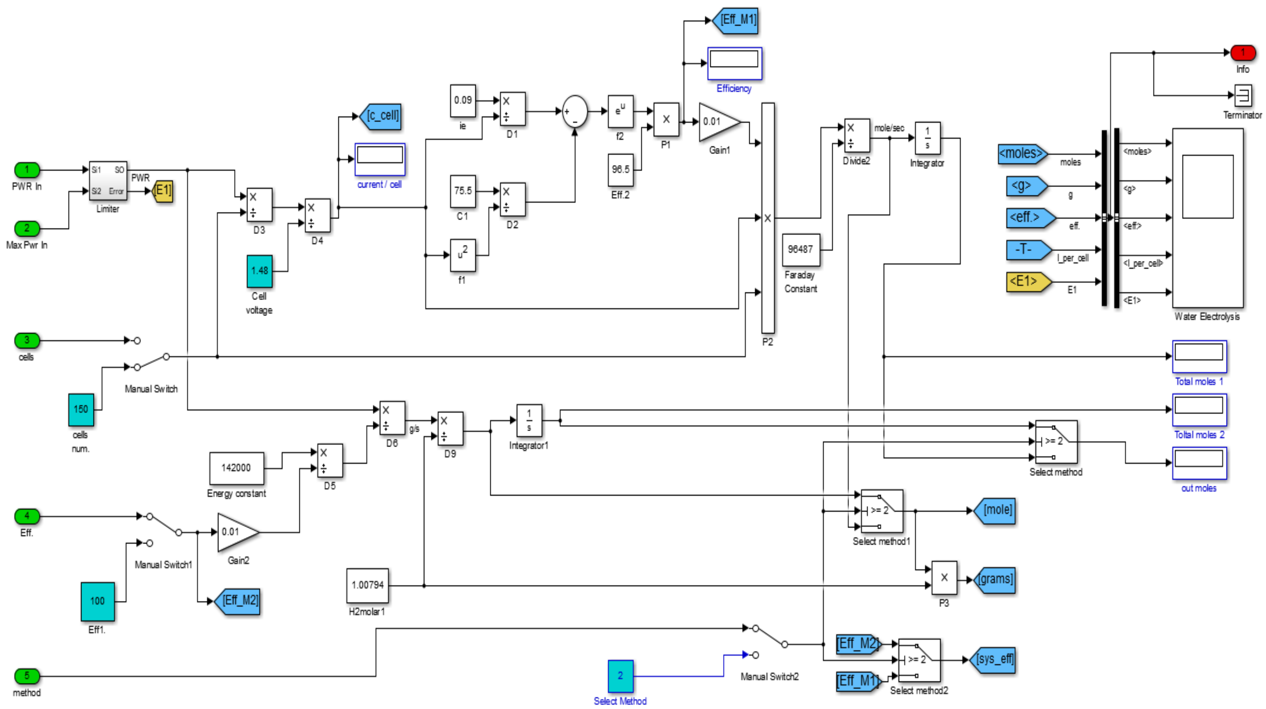


Figure 3-3 Water Electrolysis subsystem Scheme

After hydrogen is generated, it requires a storage with certain parameters. The maximum capacity of the used storage is 30 kg which can supply alone a load of 10kWh for 4 days and 22.3 hours if a fuel cell of 100% efficiency is used. The hydrogen storage model core is based on a model described in [70]. This storage model is denoted by

$$Pb - Pbi = \frac{Z*NH2*R*Tb}{MH2*Vb} \qquad (3\text{-}10)$$

where $P_b$ is the tank pressure, $P_{bi}$ is the initial pressure, $Z$ is the compression factor, $N_{H2}$ is the hydrogen amount in moles, $R$ is the gas constant, $T_b$ is the tank temperature, $M_{H2}$ is hydrogen molar mass and $V_b$ is the tank volume. The following figure shows the design of the proposed hydrogen storage subsystem:

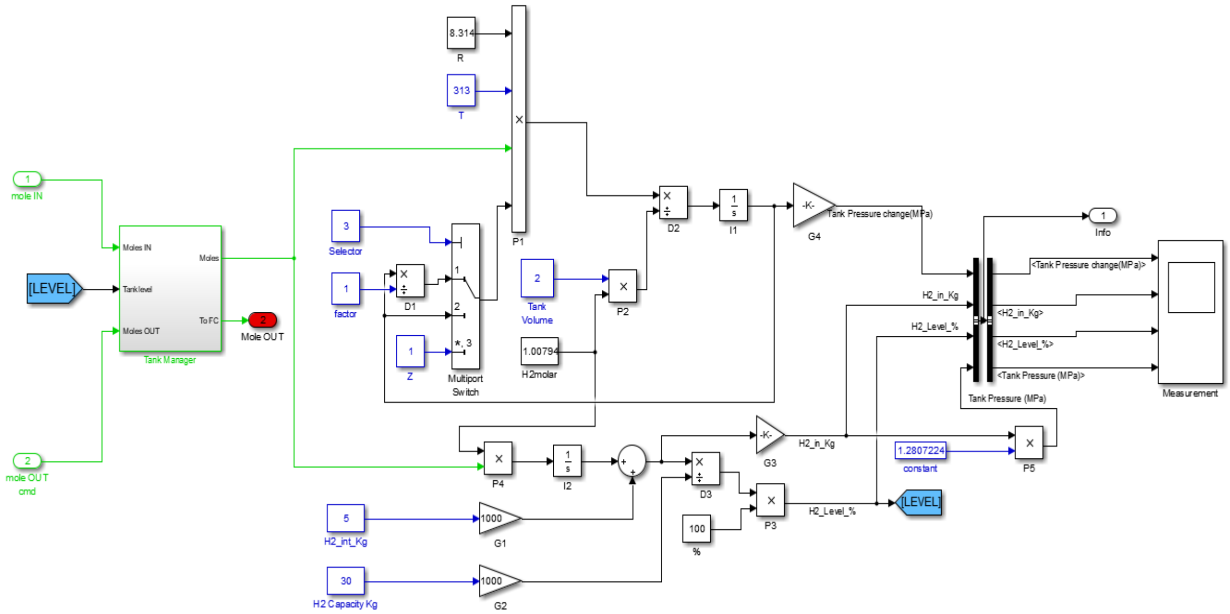


Figure 3-4 Hydrogen Tank subsystem Scheme

In discharging mode, the FLC requests fuel cells to convert the hydrogen into electrical energy to supply the load. There are many types of fuel cells. The fuel cell model used in this work is based on equation (6) in which the outputs are water, that can be recycled, and electricity.

$$\text{Electrical power generated} = N_{H2} * M_{H2} * \eta_{FC} * E_C \qquad (3\text{-}11)$$

In equation (6), $\eta_{FC}$ is fuel cell efficiency and $E_C$ is theoretical energy factor equivalent to 39.4 kWh/Kg, or 142KJ/g [97]. The following figure shows the design of the proposed hydrogen fuel cell subsystem.

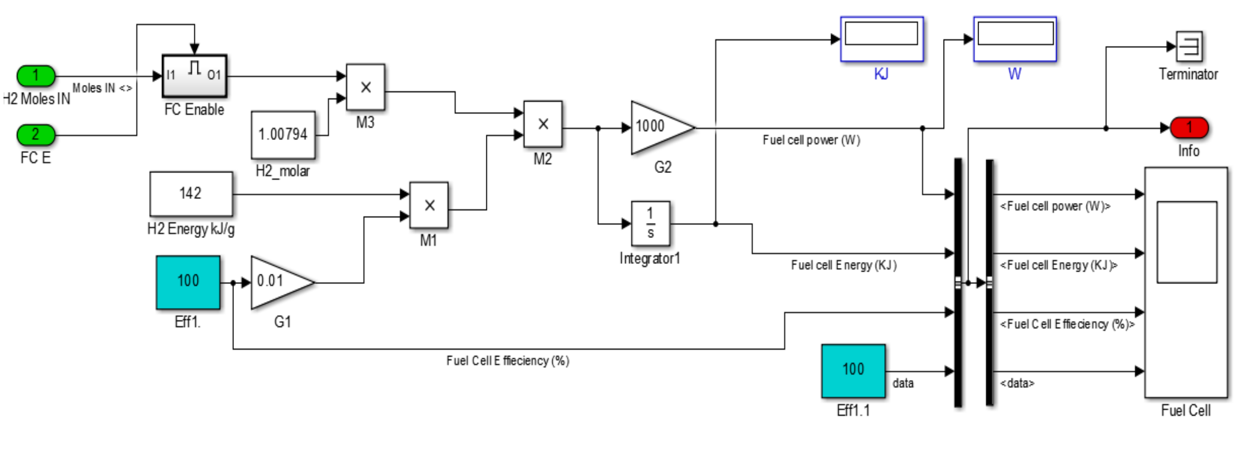


Figure 3-5 Hydrogen Fuel Cell subsystem Scheme

### 3.4.6 Demand and Load Power Subsystem

This subsystem represents the power requested from the demand side. It helps us understand how much power is required to be generated every second, therefore the system is responding to that amount. As a part of described simulations, this data is obtained from a smart meter connected to house under solar-powered house project in Alberta.

# 4. Fuzzy Logic Control

## 4.1 Introduction to fuzzy logic

This chapter discusses the fuzzy logic and fuzzy logic control systems. Then, our proposed fuzzy logic controller for the hybrid renewable energy system is discussed in details. Fuzzy logic controllers are found in a vast number of products such as washing machines, rice boiler, air condition and camera autofocus. The success of fuzzy logic controllers (FLC) is due to their ability to deal with the knowledge that is represented in a linguistic form instead of the conventional mathematical method. FLC is designed based on the experience of the expert or the system user rather than modeling the system mathematically and then try to solve complex equations as control engineers used to do conventionally. This concept gives the strength and motivation to formulate fuzzy logic as Lofti Zadeh developed and established the fuzzy set theory in 1965.

The main advantage of fuzzy logic is its ability to implement experience and knowledge of a system that is sometimes can be difficult to derive its mathematical model accurately and completely or ill-defined one or input data is not precise [98]. Fuzzy logic is a rule-based system that is designed by linguistic fuzzy rules, that relate the output command to the input data. Fuzzy rules are in the form of if-then rules where an expert should them so they will cover all possible conditions the system is expected to go through.

Any fuzzy system has four components to work as fuzzification, rule-based inference, rules, and defuzzification. Fuzzy logic can receive imprecise inputs that will be converted into fuzzy values as a degree of membership of linguistic fuzzy sets then the rule-based system will infer the proper result. the output linguistic value based on the rules and the inference type (here using Mamdani inference) will be the fuzzy output result that requires a defuzzification process which converts these linguistic values to real values (most defuzzification process used is center of the area, COA).

The rules are based on expert experience and it is a collection of if-then statements that contain all information for controlling the system. The fuzzy algorithm includes 25 fuzzy rules as shown in table 1. The fuzzy inference engine is the heart of the fuzzy system and it makes a logical decision based on fuzzy sets and the result is fuzzy linguistic value. The following figure shows the full components of the fuzzy logic system:

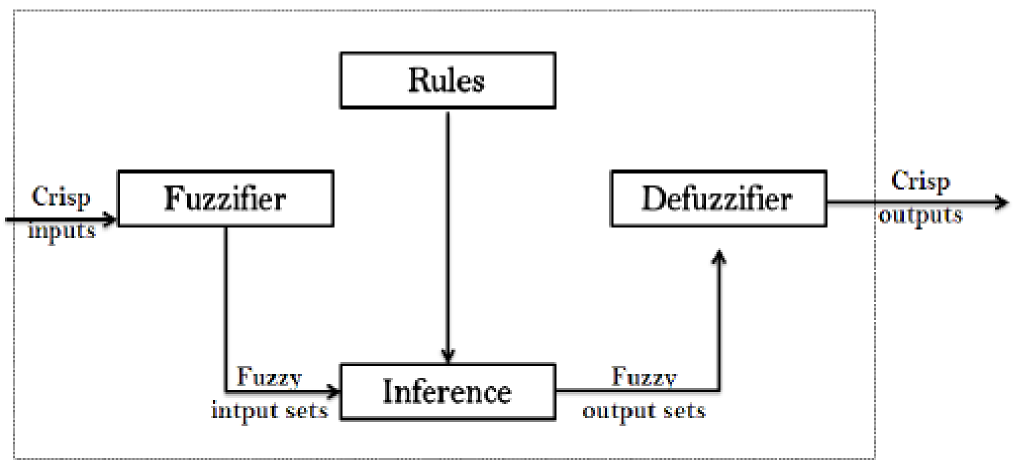


Figure 4-1 Fuzzy logic system block diagram [99]

## 4.2 Fuzzy Control System Design

The function of a control mechanism is to maintain certain goals from the system at different desired values. The ideal control system is a linear system which relates its inputs directly to the outputs. Nevertheless, in practice, instabilities affect the system output being controlled and cause deviation from the proposed set points. The control mechanism is divided into two main designs as an open loop system and a closed loop system. The closed-loop system uses the signal feedback to correct the controller output to meet the desired value. The study of control theory includes the major control characteristics such as stability, accuracy, the speed of response, sensitivity, and representation [100].

Controlling a system complex as HRES is difficult to achieve using conditional methods. Therefore, FLC is a more suitable solution since it covers a high range of possible working situations with an acceptable level of uncertainty or lack of future information. FLC is reasoning is more close to the human approach to decision making which gives the FLC the priority to be selected for controlling a complex system as HRES.

## 4.3 Proposed Supervisory Control Design

The system is very dynamic, nonlinear, unpredictable, has a lot of uncertainty and its mathematical model is somehow complicated so the best choice is to use one of the expert-based systems, intelligent, such as fuzzy logic. The fuzzy logic will manage the flow of energy throughout the system to assure high-quality uninterruptible power delivery to the demand regardless of intermittent in the power generation. The controller has three main states as discharging mode which allows battery and hydrogen fuel cell to support the load, balance mode when supply power equals demand and controller at rest, and lastly, charging mode that allows battery and water electrolysis receive an excess of energy and store it to be used later.

The rules are designed based on system requirements and modified by trial and error. Matlab and Simulink are used to model, test, and analyses the system. The proposed controller consists of two operational modes: charging and discharging mode. Each mode has a fuzzy logic controller, as shown in the following figures, respectively.

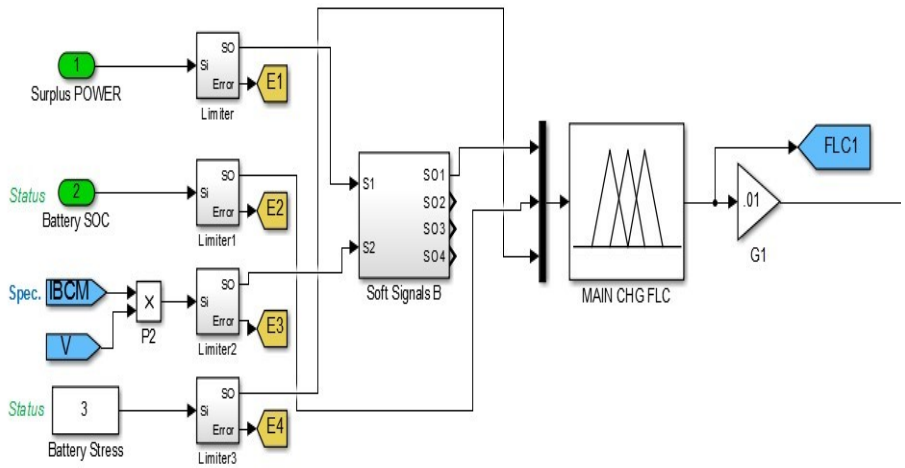


Figure 4-2 Fuzzy Logic Controller Design

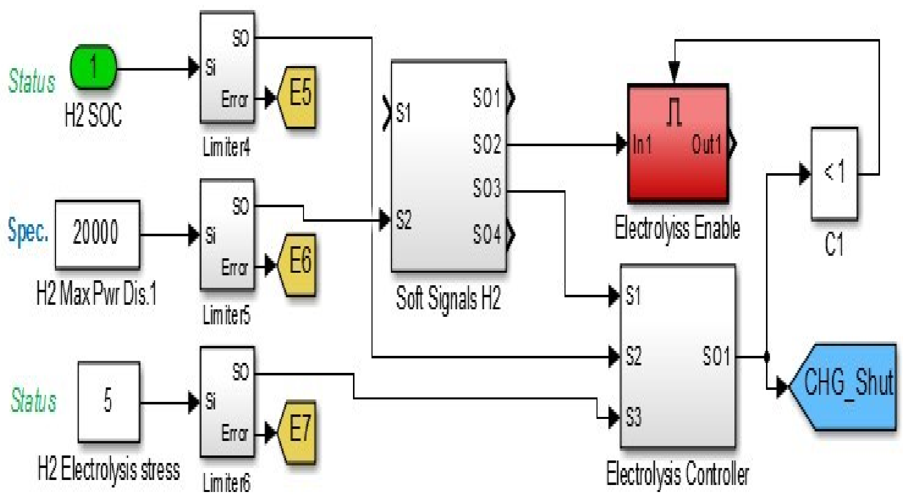


Figure 4-3 The Hydrogen Controller

The charging mode is responsible for charging the batteries and/or for generating hydrogen fuel from the surplus power, while the discharging mode discharges the batteries and/or generates power from a hydrogen fuel cell to support the load.

Let $P_{ESS}$ represent the power to the energy storage system, while the solar power is $P_S$, $P_W$ equals the wind power and $P_D$ the demand power. Then, the power that goes to the energy storage system is given by

$$P_{ESS} = P_s + P_W - P_D \tag{4-1}$$

$P_{ESS}$ is either a positive (surplus) or negative (required) power.

### 4.4.1 Charging Mode

Charging mode is activated when $P_{ESS}$ is positive, indicating surplus power. The decision of distributing the surplus power is achieved and implemented by the FLC that uses three inputs. Based on 38 rules, the FLC generates an output signal that assigns a percentage of the surplus power to the battery and the remaining power goes directly to hydrogen controller, which decides whether this power goes to the water electrolysis or to the dummy load. Hydrogen controller is required to protect the water electrolysis from overpowering and protects the hydrogen storage tank from generating hydrogen when it is full. The three input signals to the fuzzy controller can be described as follows.

Input one ($x_1$) is the ratio of surplus power to maximum battery charging power. It can be expressed in terms of the battery maximum charging power ($P_{BMC}$) as

$$x_1 = P_{ESS} / P_{BMC} * 100 \qquad (4\text{-}2)$$

$x_1$ is designed to understand how large the surplus power is, compared to the maximum power with which the battery can be charged. This principle is crucial for protecting the battery from large current when it is nearly full. It should be noted that $x_1$ is limited between 0 and 100.

Input two ($x_2$) is the battery state of charge that informs the FLC about the level which the charge of the battery has reached. Value of $x_2$ is also in the range of 0 to 100.

Input three ($x_3$) represents battery state of health (SOH). It describes how stressed the battery is, at a certain time. It is therefore an important input for the FLC. Based on data of the signal received from $x_3$, the FLC avoids charging the battery with higher current rates when the battery is exhausted. The input $x_3$ is represented as a scale of ten.

The three inputs are crucial for protecting the battery. They protect it from a short lifespan by avoiding rapid aging as well as avoiding damage to the battery.

By using fuzzification process, the input signals are converted into membership functions. The fuzzy membership functions and fuzzy rules are designed to charge the battery within safety limits based on the following constraints:

$$SOC_L = 15\%$$

$$SOC_H = 95\% \quad (4\text{-}3)$$

The safety limits are implemented in the rules which relate the inputs with the proper output in the figure.

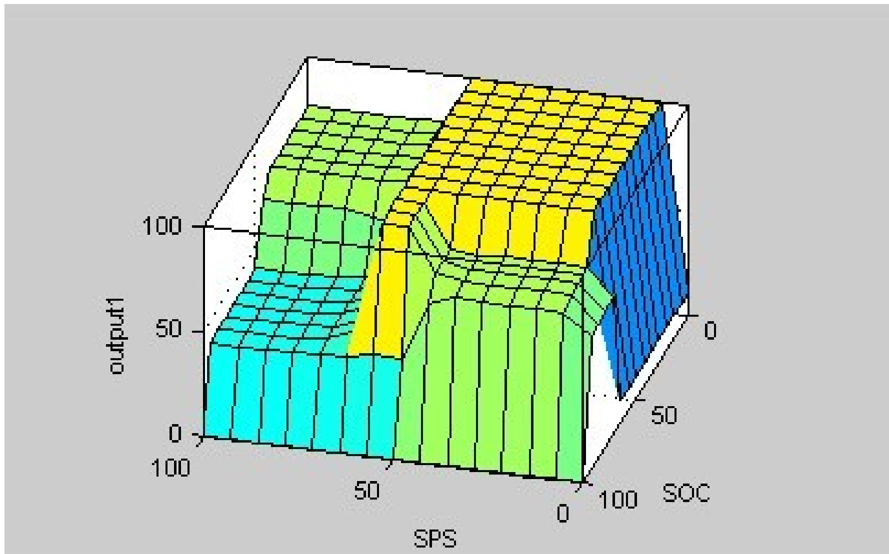


Figure 4-4 charging mode fuzzy controller rules surface

The rules and memberships are then modified by observing the controller output based on a process to implement human experience within the controller. Thereafter, the FLC controller generates an output signal which is a variable from 0 to 1. The output signal is eventually multiplied by the surplus power and fed to the battery while the remaining power goes as an input to the hydrogen controller. The hydrogen controller has four inputs. These inputs are the respective minimum and maximum power received by water electrolysis, the electrolysis health status and hydrogen tank level.

The objective of the first controller is to make sure that the hydrogen tank is not full or does not exceed a certain threshold. The controller will then assign the power to the water electrolysis within the maximum range of power that electrolysis can receive. However, if power is higher than the limit, or the hydrogen tank is full, or the electrolysis health status is bad, the power will go directly to a dummy load. The quantity of generated hydrogen depends mainly on the efficiency of the water electrolysis.

Out of this mode, the power going to load, $P_L$, is given by

$$P_L = P_D + P_{DL} \quad (4\text{-}4)$$

where $P_D$ is load demand and $P_{DL}$ is powera of the dummy load.

### 4.4.2 Discharging Mode

As an opposite of the charging mode, the discharging mode is activated when PESS is negative, a case where there is no surplus power, but this time, power is required to satisfy the load. Similarly, in the previous case, the decision of distributing the required power is done by the FLC which is the main controller in the discharging mode. This fuzzy controller uses three inputs. Based on 31 rules, it generates an output signal that assigns a percentage of the required power to the battery and the remaining power is requested from the fuel cell after passing hydrogen controller that decides whether the FC can support the load. If the FC cannot support the load, the system shuts down to avoid low output power quality. Hydrogen controller is required to protect the fuel cell from over discharging and to avoid power quality deficiency. In the discharging mode, of the fuzzy controller also has three input signals, which are $x_4$, $x_5$ and $x_6$ similar but opposite in definition and function to the charging mode.

Input $x_4$ is the ratio of needed power to maximum battery discharging power ($P_{BMD}$):

$$x_4 = P_{ESS} / P_{BMD} * 100 \quad (4\text{-}5)$$

In the discharging mode, $x_4$ determines how large is the needed power compared to the maximum power that battery can deliver. This is crucial to protect the battery from over discharging. In the discharging mode, $x_4$ remains limited to values in the range of 0 to 100.

Input two ($x_5$) and input three ($x_6$) maintain their same respective definitions and functions as well as ranges as discussed in the previous section.

Additionally, the input signals are also converted into membership using fuzzification process and all fuzzy membership functions and fuzzy rules are designed to save the battery from damage using information extracted from lithium-ion battery charging/discharging curves. The rules are illustrated in the figure.

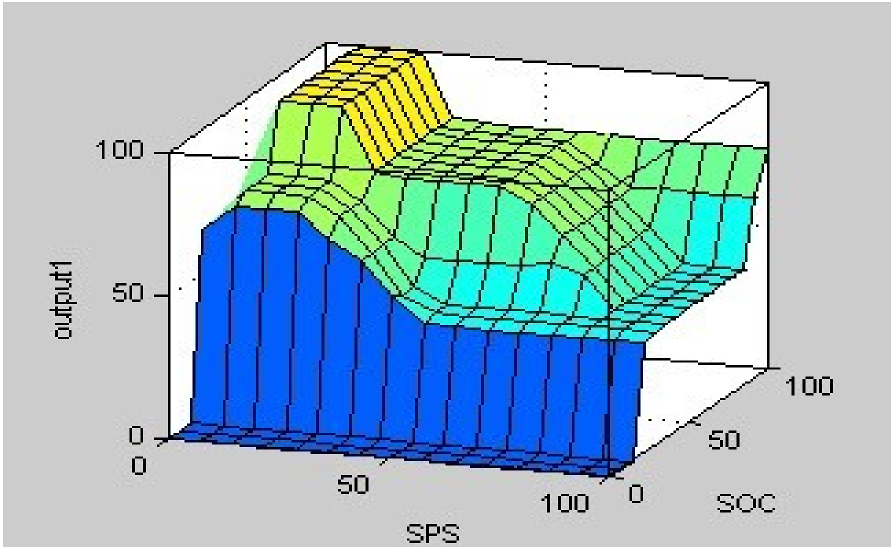


Figure 4-5 Discharging mode fuzzy controller rules surface

The controller outputs signal, within the range of 0 to 1, is multiplied by the required power to request this amount from the battery. The battery will therefore discharge and generate the amount of power that is subtracted from the required power to determine the new value of power from the FC. If the requested power from the FC is not higher than the maximum power that fuel cell can generate, the fuel cell will respond and generate electricity. The quantity of hydrogen used depends on the efficiency of the fuel cell. However, if the hydrogen tank is empty (or below a certain threshold), or the FC health status is bad, the system will shut down due to inability to supply the load. In the discharging mode, the power going to load is

$$P_L = P_s + P_w + P_B + P_{FC} + P_{DL} = 0 \quad (4\text{-}6)$$

where $P_s$ is solar power, $P_w$ is wind power, $P_B$ is battery power, $P_{FC}$ is fuel cell power and $P_{DL}$ is power of the dummy load.

# 5. Results and Discussion

In order to test and qualify the proposed HRES model, simulations are to be conducted on the full model with several scenarios such as providing a full year scenario where feeding the system with real data of solar, wind and house demand powers and see how the controller manage the power flow between various subsystems. After that, simulating the system under various power supply charging and power demand discharging separately to monitor the battery behavior in deep details that are usually not visible in full-year simulation since the battery charging and discharging behavior is well clear in small time steps with high data resolution. However, before conduction simulation, data analysis is essential to understand the type of environment the system in and have a rich information about how solar, wind and demand are behaving and varying during diverse months of the year.

Simulations were performed using the smart power system illustrated in chapter 3 section 4. The system consists of 10 kW wind power, 10 kW PV solar power, 5kWh lithium-ion battery bank, 10 kW Water Electrolysis, 10 kW fuel cells, 30kg hydrogen tank and a 10 kW maximum power supply capacity. Performed simulations confirm the ability of the controller to satisfy the main goal of the of this work: to supply the load at all times using solar and wind power (which are fluctuating renewables), through the assistance of batteries and hydrogen fuel cell without a reduction in the power quality or load supply deficiency. The simulation results also verify fulfillment of the second objective: to operate the battery in a proper manner and to protect it in both charging and discharging modes.

## 5.1 Model Data Analysis

In this section data collection of house demand, solar and wind power will be discussed. The data of the year 2016 is collected from three different house projects in Alberta province that have solar PV installed on top of them. For a selected house, the house demand was recorded using a smart meter installed in the studied house. Thus, this data represents real house demand powers over the whole year. On top of this house, solar panels were installed and connected to the same meter. However, that house had not wind power turbine installed as part of the project so wind speed in that area is collected instead. Wind speed data were used to derive wind power according to typical wind power curve utilized by a leading company in wind turbines Vistas to calculate the turbine output power. The typical wind power curve can be mathematically modeled using polynomial regression taken from [101] as shown in the following equation.

$$P(j) = -0.0103k(j)^3 + 0.3866k(j)^2 - 0.3578k(j)^1 - 3.2417 \qquad (5\text{-}1)$$

This equation works for wind speed from 3.5m/s to 14 m/s. The wind speed to wind power was done utilizing the following curve [102]:

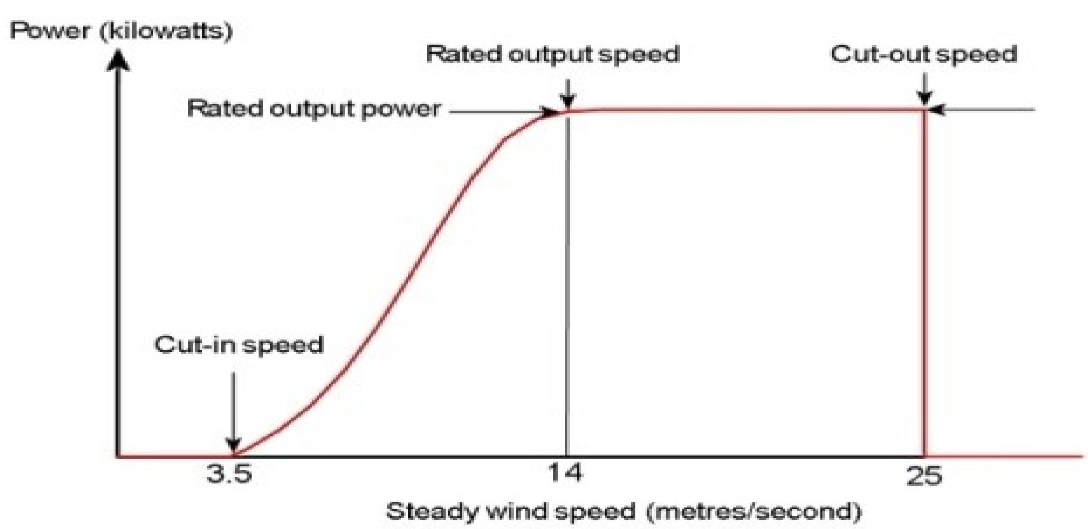


Figure 5-1 Typical Wind Turbine Output Power curve [100]

All wind turbines have a power curve that relates the performance of the turbine over a range of wind speeds. This curve can be drawn when testing the wind turbine at various speeds [103]. The wind speed can be plotted as three distinct regions of the generated power as the following:

Region one: this region has the range of low wind speeds below 3.5m/s and the turbine will not be able to produce any power due low wind energy supply to spin the rotor.

Region two: this region represents the intermediate range of wind speeds where the generated power is proportional to wind speed. Equation 5-1 relates the output power with wind speed using polynomial regression.

Region three: this region the wind turbine will operate at its rated power regardless of the value of wind speed. This caused the curved to be flat overall wind speed value till the turbine reached the dangerous speed and require a shutdown to secure the turbine from damage.

After that wind power can be obtained through a m-file in Matlab. Later after having wind power data ready, changing its resolution to 15 minutes to match other data. As a final step before analyzing collected data, they require scaling to match them to the proposed criteria of a 10kw maximum demand, solar supply, wind supply and system maximum delivering power. The battery is designed to be between these ranges for the purpose of testing the system reliability. Next step is to analyze the collected data to see their maximum, minimum and monthly average values. The resolution scale is 15min and for full-year simulation, it is one hour.

After analyzing 2016 demand, solar and wind data for a location in Alberta, three figures were plotted to illustrate the energy production and consumption distribution over the year. It is noticeable from the solar power generation figure that the maximum average peak of solar production, sunniest month, occurs in June at 1 pm of 7 kW followed by July as the second average high peak of 6.5 kW while the three months of April, May and August have a maximum average peak of around 6 kW at the same time of the other peaks. All these months have a peak value greater than 5 kW which is higher than half of the solar power installed capacity of 10 kW. The remaining months have lower average peak values and the lowest solar production value occurs in January at surround 400 Watt. The solar power distribution over the 24-hour period is almost similar during all months as a bell shape.

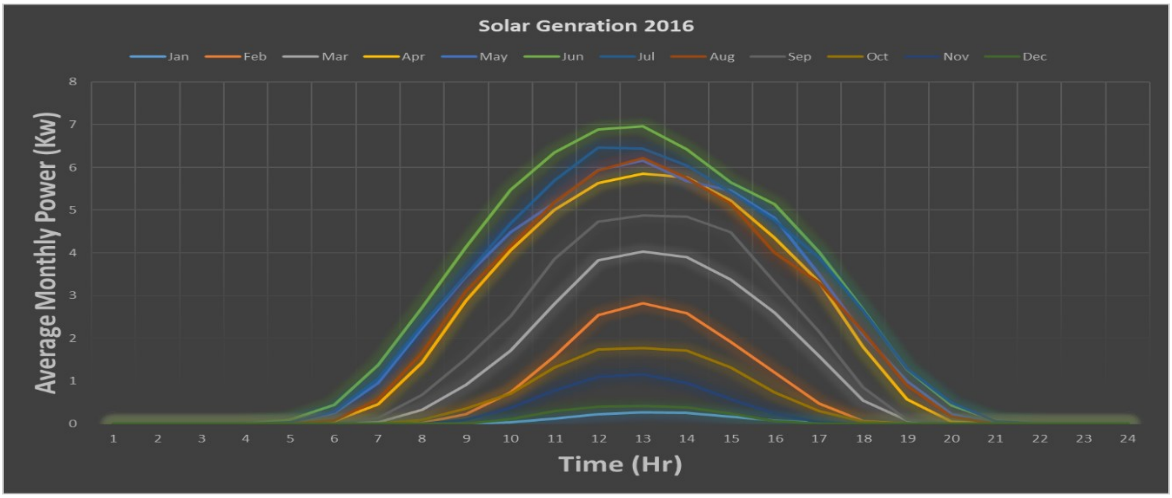


Figure 5-2 Solar power generation 2016

However, wind production in this region is relatively high compared to solar production as the minimum average power in all months exceeds 6 kW and reached up to 9.5 kW and the wind power value oscillates between these values in all months. The higher wind generation happened in February and the lowest one happened in January, August, and October. The next figure illiterates the average wind power distribution during the day of each month. In all months, the wind is distributed over the day with very similar pattern.

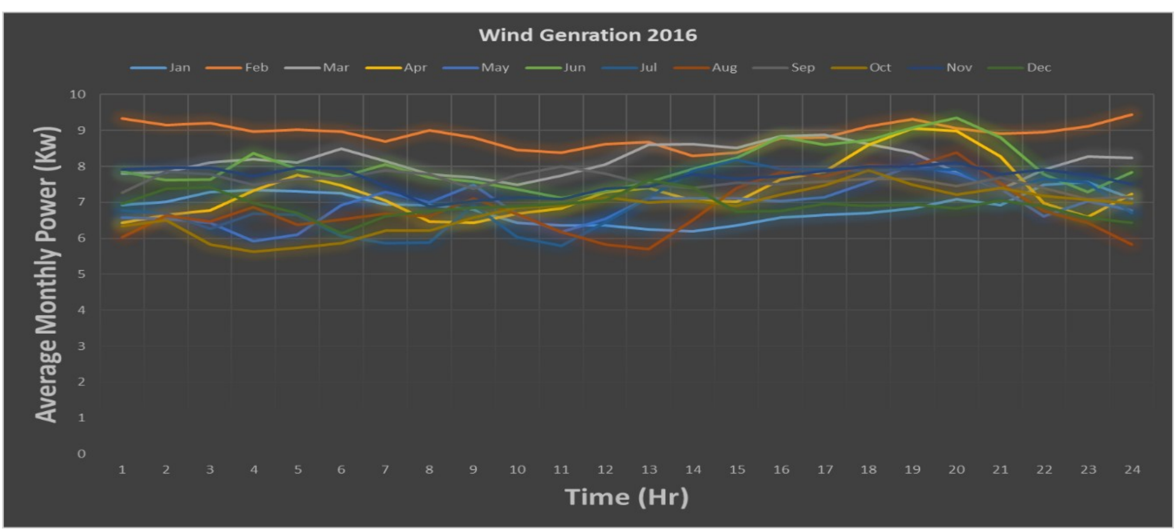


Figure 5-3 Wind power generation 2016

On the other side, house demand extreme values are changing from month to month but have almost identical pattern over the 24-hour period. The house demand has a constant baseload of 356 Watt throughout the year. This minimum load could be due refrigerator or basic light usage. The house demand varies during the day and has at least two peaks that occur at separate times of the day. Here are some observations from House demand figure. House demand increases after 7 am to a first daily peak that occurs around 9 to 11 am and then it goes back to a lower level till the second peak occurs at around 5 pm and its maximum between 7 to 8 pm. Then the demand decreases till it reaches a lower constant level overnight. November and December have higher average values in the first peak at around 5 kW and 3.3 kW consequently. While January has the highest average value in the second peak of 3.78 kW. The rest of months are almost behaving in the same pattern except September which has a lower level of demand between the first and second peaks.

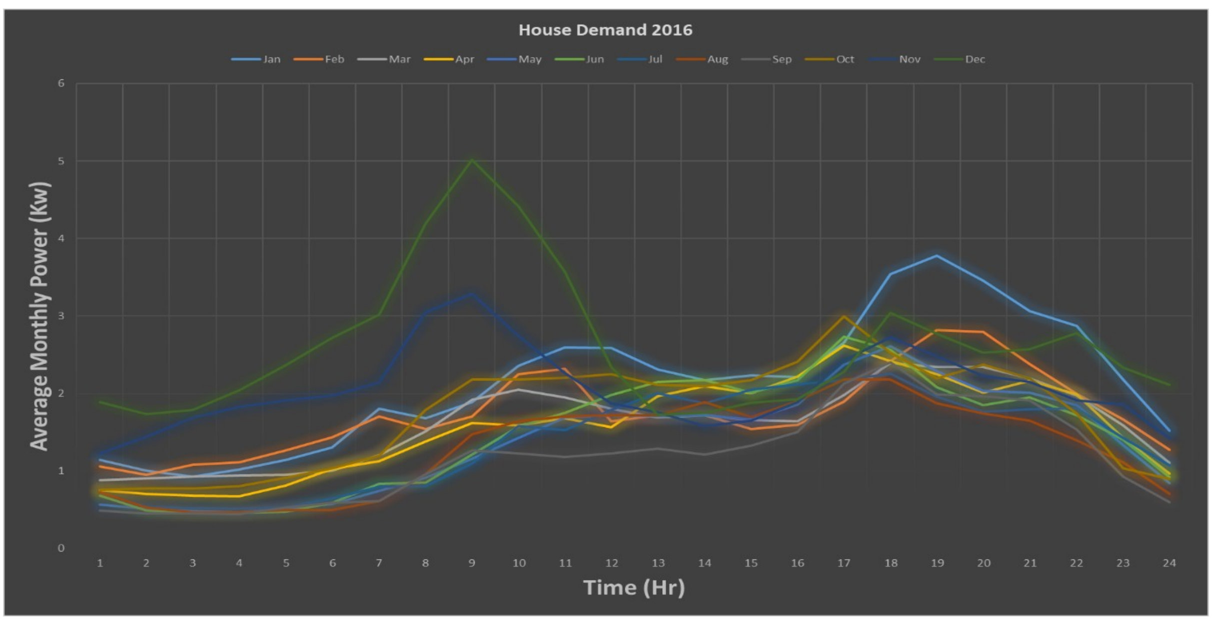


Figure 5-4 House demand 2016

The following table is showing the maximum and minimum power rates of solar, wind and demand every month. The maximum demand of 8474 Watt occurred in December followed by four high demands above 7 kW in January, October, and November. This high peak tells that this house consumes high power rates on certain days in the winter season. The remaining months have a maximum demand around 4.5 kW which assist the idea of having at least 5 kWh energy storage system as part of the HRES. The house minimum consumption happened in June with 334 Watt usage. Now concentrating on the generating side of the system. It is clear that wind is reaching the maximum capacity at least once a month. While solar maximum varies as low as 1130 Watt in December to the peak in May of 9892 Watt. The high other peaks take place from April through August which represents the summer season. The minimum solar power reaches zero every day because of sun absence at night.

**Table 5-1 Maximum and minimum values of collected data**

| MONTH | MAX HOME POWER DEMAND (W) | MIN HOME POWER DEMAND (W) | MAX SOLAR POWER (W) | MIN SOLAR POWER (W) | MAX WIND POWER (W) | MIN WIND POWER (W) |
|---|---|---|---|---|---|---|
| **JAN** | 7370 | 356 | 3086 | 0 | 10000 | 0 |
| **FEB** | 5704 | 356 | 5824 | 0 | 10000 | 0 |
| **MAR** | 5360 | 376 | 7646 | 0 | 10000 | 0 |
| **APR** | 6686 | 378 | 8422 | 0 | 10000 | 0 |
| **MAY** | 4974 | 354 | **9892** | 0 | 10000 | 0 |
| **JUN** | 5706 | **334** | 9120 | 0 | 10000 | 0 |
| **JUL** | 5356 | 406 | 9010 | 0 | 10000 | 0 |
| **AUG** | 6356 | 376 | 8690 | 0 | 10000 | 0 |
| **SEP** | 4578 | 356 | 7232 | 0 | 10000 | 0 |
| **OCT** | 7158 | 394 | 6328 | 0 | 10000 | 0 |
| **NOV** | 7730 | 470 | 3494 | 0 | 10000 | 0 |
| **DEC** | **8474** | 466 | 1130 | 0 | 10000 | 0 |

## 5.2 2016 Full-Year Simulation Scenario

The drive of this scenario is to make sure that the system will be able to run through all 2016 full-year data without interruptions, errors, and bugs. Also, to observe the overall system behavior in the long run through various months and comment on the results. And to make sure that the controller achieves the recommended goals. The scenario started by converting the 2016 full-year data into one-hour resolution and then to feed them to the HRES model. The HRES model is running in hours and is using dynamic sampling rate which helps the solver maintains lower sampling rate for events that can happen in a fraction of an hour instead of the one-hour sample rate. The dynamic sampling rate enables the solver to derive best solution quality and run the simulation in a shorter time. The simulation was done several times and each time it requires small errors fixing and interruptions solving. Later, after all errors fixing, the simulation ran smoothly and took more than three hours, simulating 366 days, to complete. Therefore, simulation data were generated and ready to release some information. The first variable to observe was the battery state of charge. As per control algorithm design, the battery state of charge shouldn't exceed 95% as a maximum full charge and shouldn't be below 15% as a maximum full discharge. The following figure illustrates the battery state of charge during the full-year simulation:

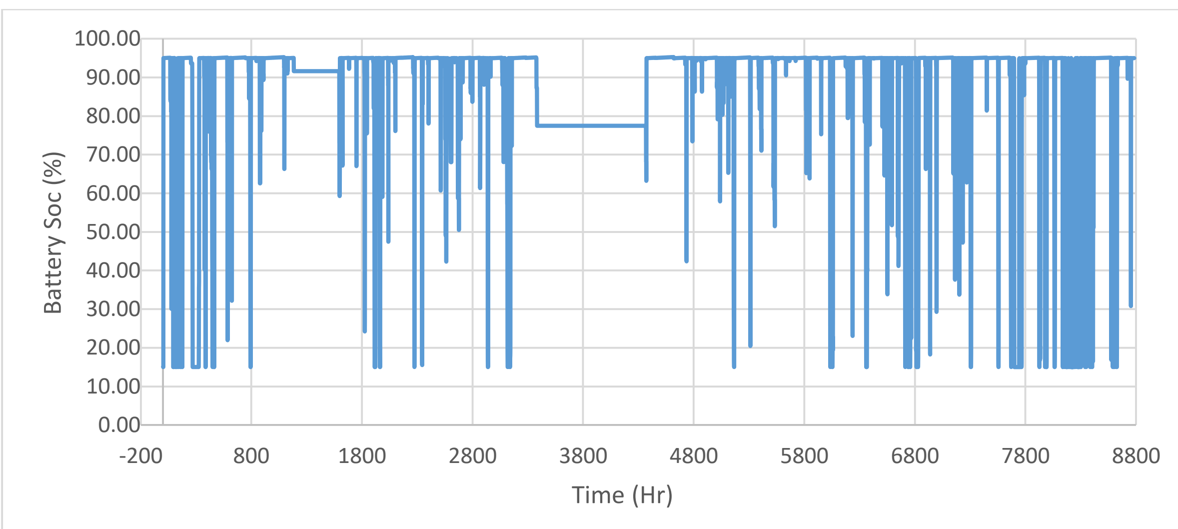


Figure 5-5 Battery state of charge during the full-year 2016

It can be seen that the battery state of charge starts from 15% to 95% and staying away from extreme limits that the control algorithm design bounds them. Although this figure shows the operating range of the battery SOC, it doesn't show the power that either consumed or supplied by the battery. For that reason, the following two figures are essential to show the battery charging and discharging behavior. The first figure explains the charging power that the controller assigns to the battery all through the year. The maximum charging power is 2C which is 10kw and the controller rarely exceeds charging the battery with more than 1C. From the figure, the events of charging the battery over one C occur few times and latest months seem to have them.

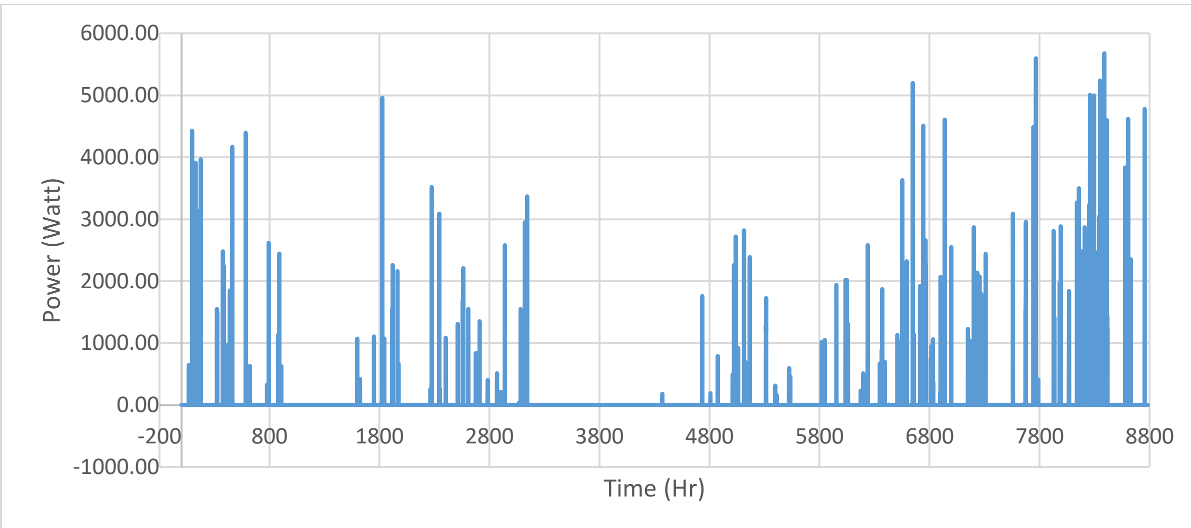


Figure 5-6 Battery charging power during the full-year 2016

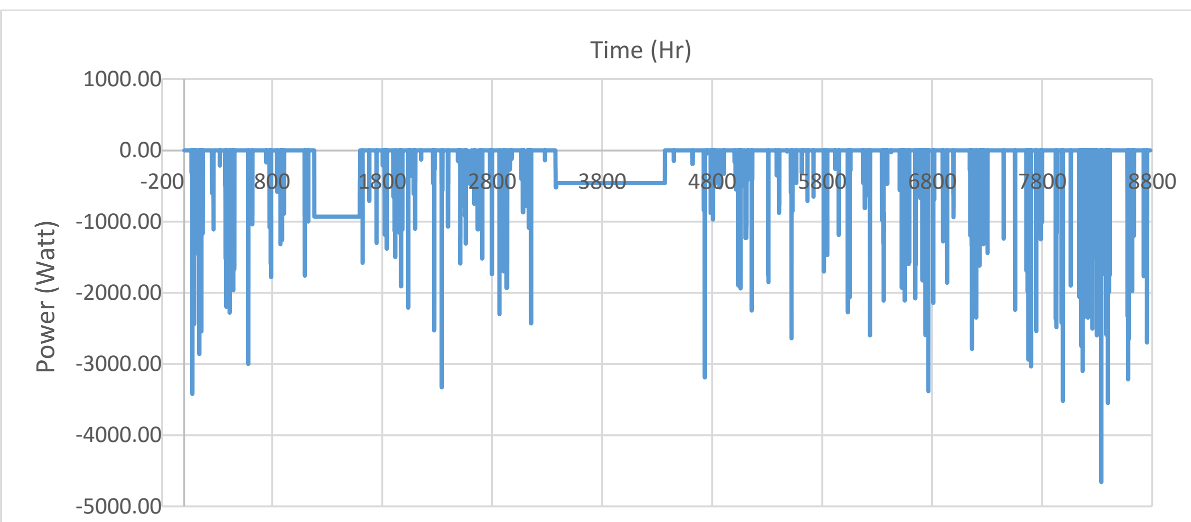


Figure 5-7 Battery discharging power during the full-year 2016

The second figure shows the discharging rate of the battery. The controller design allows the battery to discharge as much as twice of its capacity. However, during the discharge of the battery in the simulation, it is noticeable that the maximum discharge event didn't surpass the battery capacity of 5 kW which saves the battery lifetime. Even more, this discharge happened once and the controller attains the strategy of less deep discharge to conserve battery health over the long run. Most of the time the controller discharges the battery under 2.5 kW or 0.5C.

On the other side of the system, the hydrogen system assists the battery and work simultaneously with. The hydrogen tank capacity is 30kg (1183.3 kWh) which is enough to power the house with full 10 kW rate for around five days with zero supply from solar and wind sources. The tank started initially with 15% of stored hydrogen which can generate up to 177.5kWh of energy when using a fuel cell of 100% efficiency. In the simulation, the controller supplies a percentage of surplus power to water electrolysis to increase hydrogen availability and store it for long-term purpose. This stored hydrogen can reach up to a maximum designed level of 95% of the full tank capacity before the controller decides to stop supplying water electrolysis subsystem and rather supply that power to either the battery or a dump load. The following figure shows the hydrogen tank level during the simulation period and it is easy to realize that the hydrogen tank remains almost near full which indicates that the full system is receiving more power than required one by the house demand.

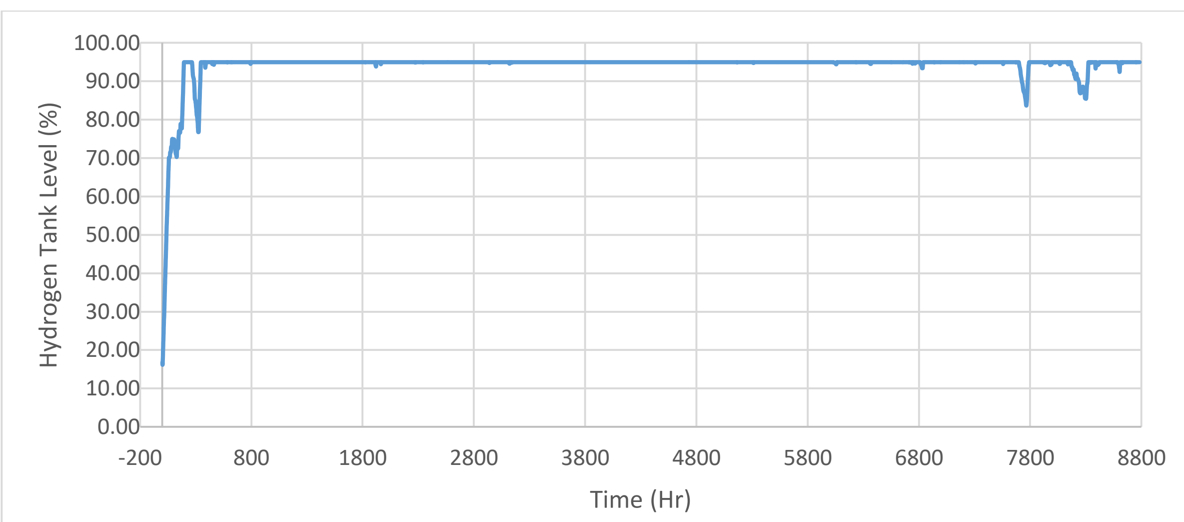


Figure 5-8 Hydrogen tank level % during the full-year 2016

The next figure provides details about the process of generating and using hydrogen. The generating of hydrogen was very high at the beginning of the year due to lots of surplus power and a low level of hydrogen tank. Then once the tank is full, the water electrolysis process stopped by the controller and wait for a power requested from the hydrogen tank. The fuel cell generates power when the battery SOC is low or the load is high or both. The latest months draw more power from the hydrogen tank than the rest months.

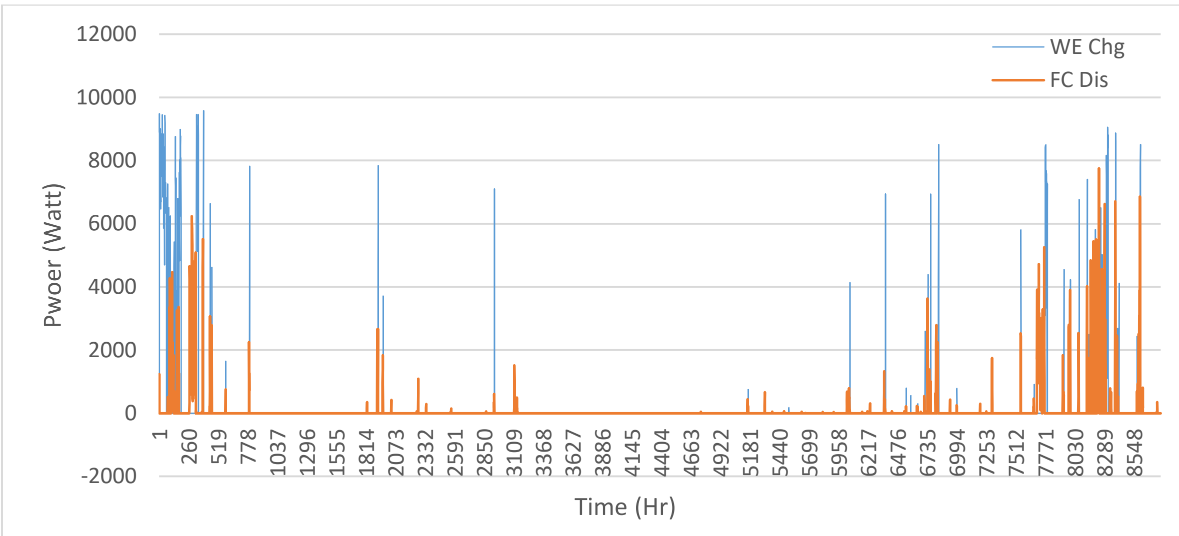


Figure 5-9 Hydrogen Generation and consumption during the full-year 2016

The difference power between supply powers and house demand goes to or come from energy storage system. This storage system acts as the power filler when house demand is higher than supplies and load when extra power is available. By proper controlling of energy storage system, the house demand can be supplied smoothly with less distortion and more stability and system reliability. The following figure shows the power flow to and from the energy storage system in general (battery and hydrogen). The positive power indicates surplus power while the negative one represents required power by demand. The power to energy system seems to oscillate a lot during the simulation which proof that both supply and demand are highly changing and rarely match each other. There are only two long periods where the supply power is close to the demand one with a difference of 0.5 kW. It is also evident that the recurrence rate of surplus power is higher than the needed power recurrence rate.

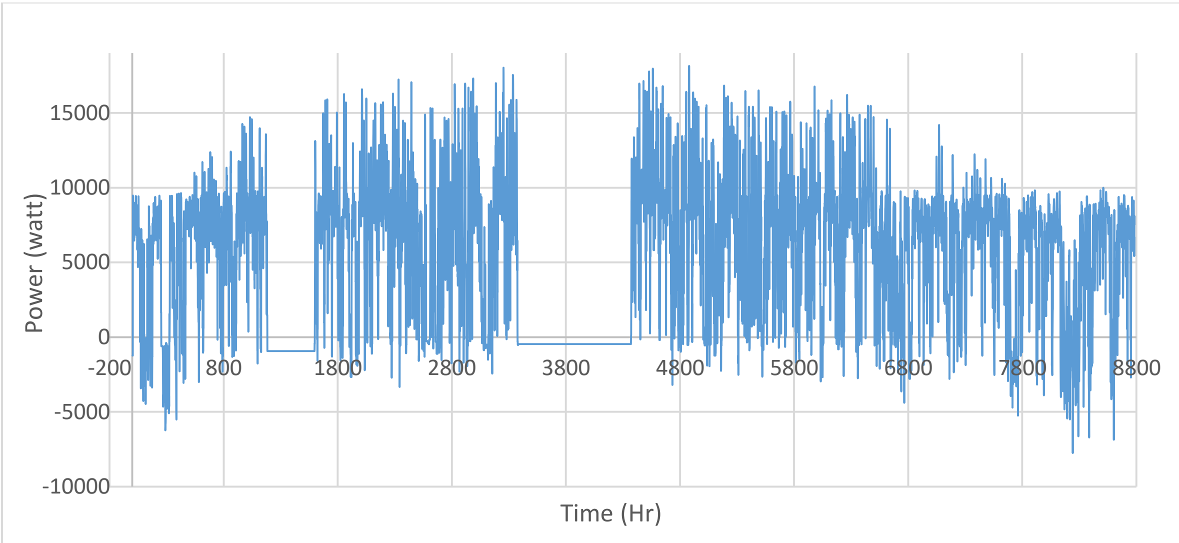


Figure 5-10 Power going to or from energy storage systems during the full-year 2016

The previous discussion was driven from full-year simulated results that have been shown in figures. However, the next section will show the average of the 24-hour variable for each month to allow the comparison of these averages and to track the system behavior among several months. This method explains the average behavior of a variable over 24 hours for a specific month.

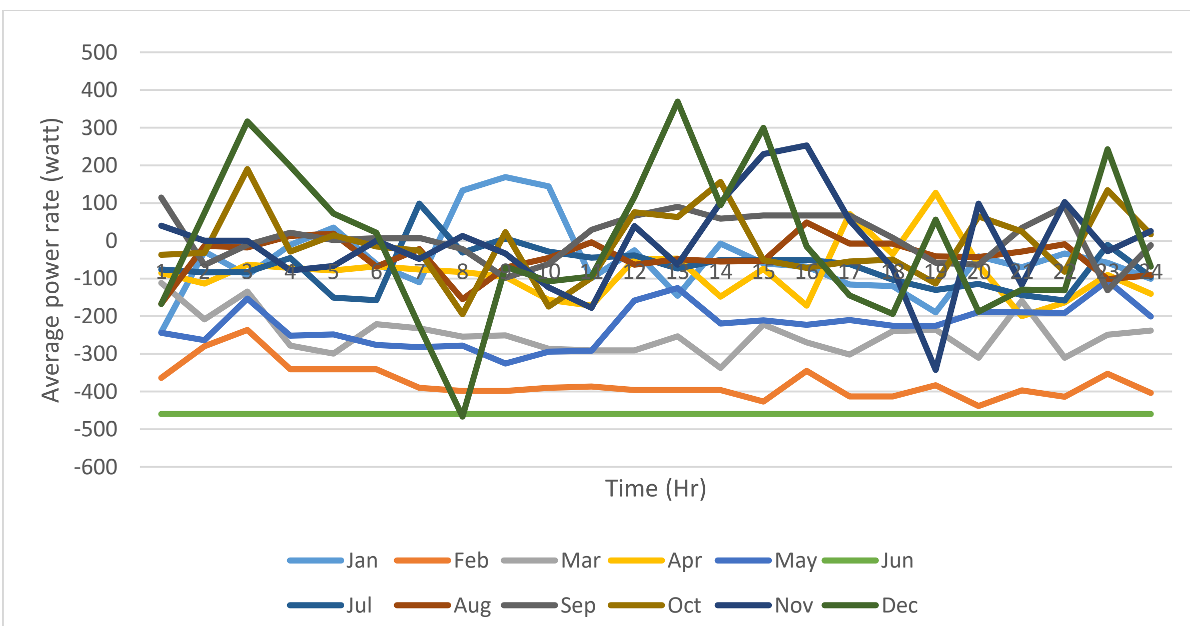


Figure 5-11 Average Battery charging and discharging power during the full-year 2016

For example, the average battery charging and discharging power rate varies during the day and also varies from month to month. The easy way to visualize this idea is to find the average value of the battery charging and discharging rate for every hour of the day through all days in one month and then draw that curve versus 24 hours. The next step is doing the same for the 12 months and put the whole curves in one figure as shown in the figure above. The above figure is rich and condenses in information which helps a lot in concentrating much information in a single file and figure.

As highlights, in October and December, the battery is highly charged in the early hours of the morning and then discharged afterward. The charging appears again at noon and is repeated two times after that till midnight. Also, it is clear that December has the highest oscillation rate between charging and discharging compared to other months. This oscillation occurs due to a big gap between supply and demand and since the battery is the short term storage it got affected first by that gap. But that oscillation value is not high with an average charging rate of 400 Watt to an average discharging rate of -450 Watt.

There are four months, February, March, May, and June, where the average battery was going negative most of the time. This means that the battery was supplying part of the load without a need to consume stored hydrogen. The other months were consuming the battery at a slight rate and charging it with small power rate too which adds a great value to use the battery in a moderate way and slows the battery aging process.

The second energy storage system consists of three subsystems as the hydrogen tank, water electrolysis, and the fuel cell. Each subsystem has an average behavior over the 24-hour period in each month. Surprisingly, the hydrogen tank average level doesn't seem to have noticeable changes during the day and the only noticeable behavior occurs in the first month. The following figure shows the hydrogen average level during the 24-hour period and shows that only the first month the hydrogen level kept raising and the other months the level stays around 95%. Having a huge hydrogen tank and lots of surplus power is the reason for small changes in the hydrogen tank level. Therefore, this figure represents general view of the hydrogen tank level despite the changes that may occur during separate days of the year.

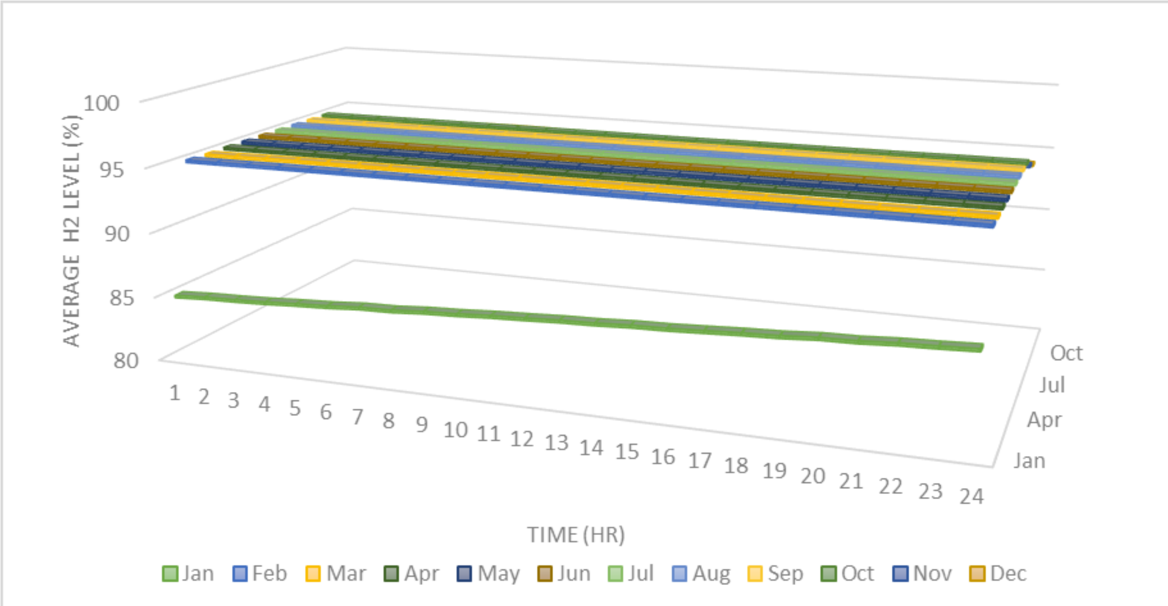


Figure 5-12 Hydrogen tank average level in 2016

The effect of a big hydrogen tank and lots of surplus power is easily shown on the water electrolysis power figure. The water electrolysis is generating hydrogen when assigned surplus power is given by the controller but when the tank reached the upper-level constraint, the controller stopped supplying the water electrolysis and deliver surplus power to a dump load to avoid hydrogen tank overflow. This control mechanism is well recognized in the below figure of average water electrolysis power. In January, the hydrogen tank starts with 15% level which gives an indication for the controller to run the water electrolysis with the surplus power. The water electrolysis charging power rate is relatively high compared to other months. When the tank is nearly full, water electrolysis process is stopped till that level goes down by the fuel cell. The same thing occurs in December when the hydrogen tank level becomes under 85% according to figure 5-13, the water electrolysis runs again filling the tank with hydrogen. A similar situation happened in November but in the other months, the utilization of water electrolysis was low with an average value below 200 Watt.

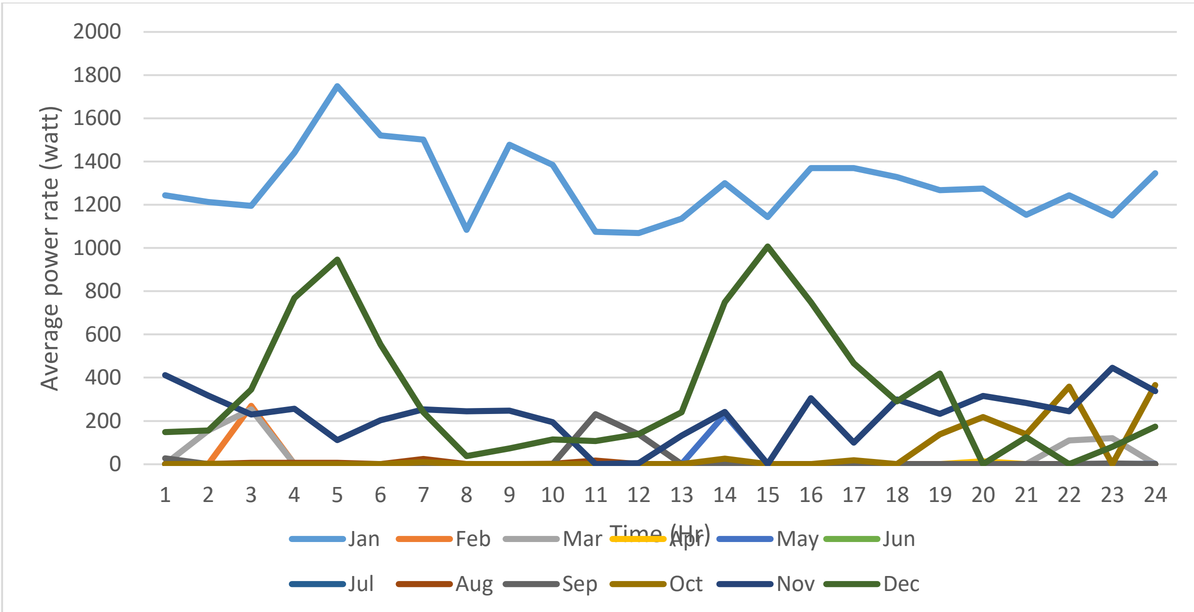


Figure 5-13 Average Water Electrolysis Charging Power in 2016

On the other side, fuel cells consume the hydrogen stored in the tank to meet the house demand in certain periods. Here are the average curves of the fuel cell power supply through the day:

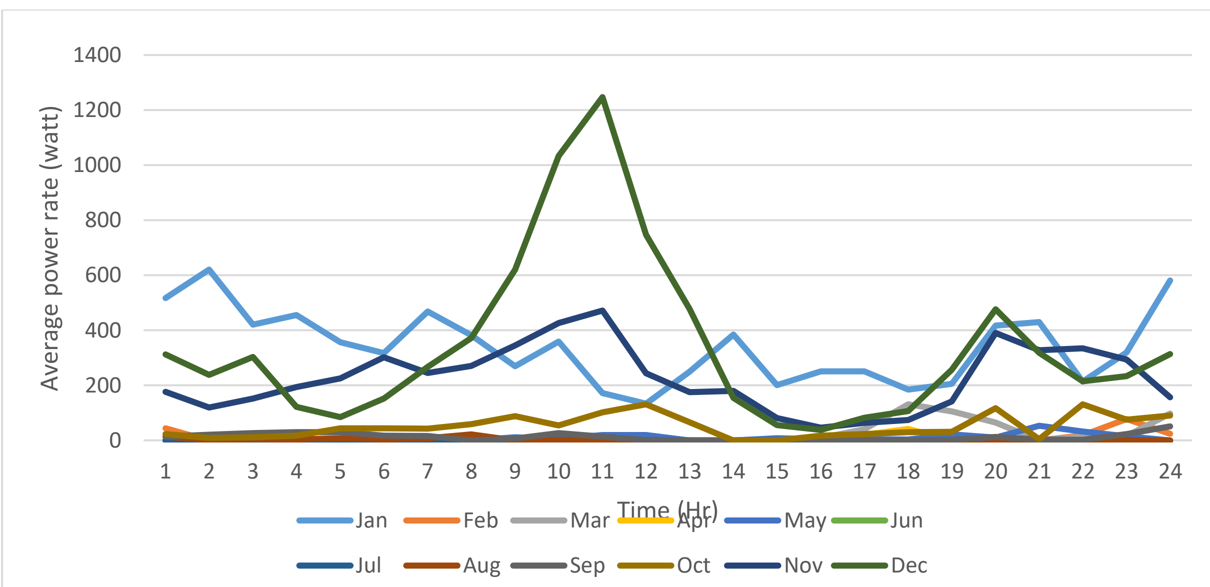


Figure 5-14 Average Fuel cells Discharging Power in 2016

From the curves, the system relies heavily on fuel cells in three months of the year (January, November, and December) due to demand increases in those months due to the winter season.

In December, an average peak occurs near 11 am with an average value of 1250 Watt and the other values remain under 600 Watt for the whole months. There is no daily pattern that can be observed from the figure which means the use of fuel cells power is distributed evenly through the 24-hour period.

Finally, the average power to ESS is displayed to perceive the amount of power delivered to the energy storage system during the 24-hour period. Almost all moths have a similar 24-hour behavior where the delivered power to ESS range from 4000 Watt to 8000 Watt. Except for June where not enough surplus power generated which push the average power in that month to the consumed part of the energy storage system.

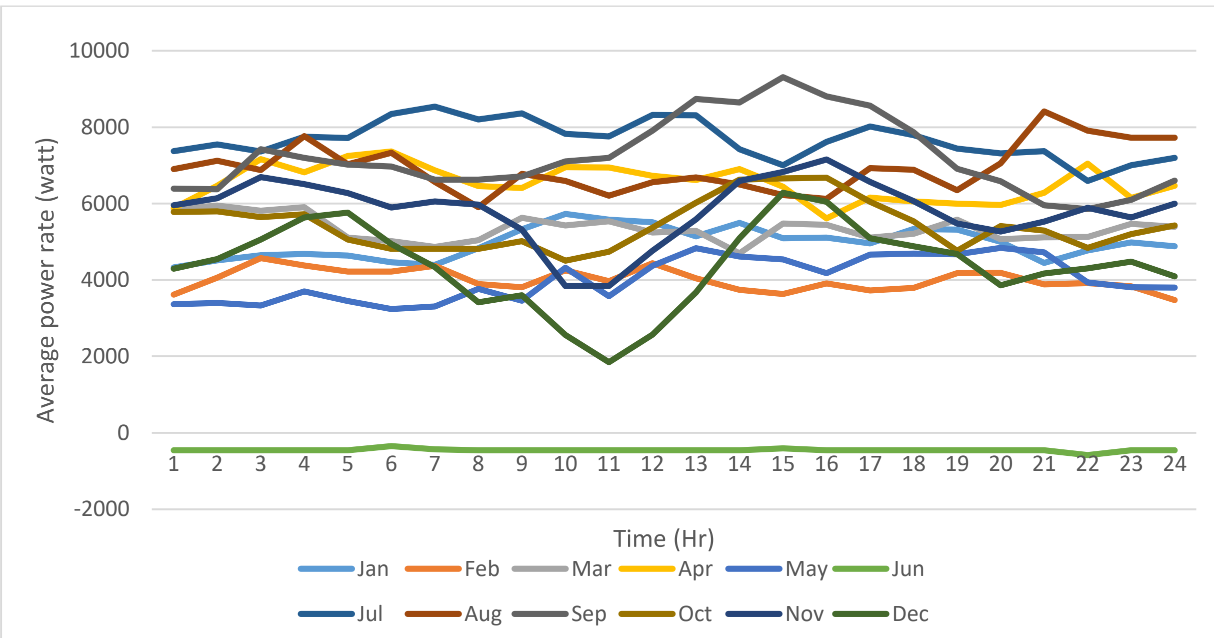


Figure 5-15 Average Power delivered to Energy Storage System in 2016

The previous discussion was on the monthly average values of several variables over a day period. However, it doesn't show the maximum and minimum values arose during the full year. The following two tables will show all the maximum and minimum values of considered variables during each month of the year. The first table is focusing on the hydrogen system which is the long-term storage element in the designed model.

**Table 5-2 Maximum Values in the Hydrogen System**

| *Month* | *max Hydrogen Tank Level (%)* | *min Hydrogen Tank Level (%)* | *max Water Electrolysis Power Supply (W)* | *max Fuel Cell Power Discharge (W)* |
|---|---|---|---|---|
| *Jan* | 95.00 | **16.13** | **9580** | 6230 |
| *Feb* | 95.00 | 94.55 | 7820 | 2250 |
| *Mar* | 95.00 | 93.86 | 7840 | 2670 |
| *Apr* | 95.00 | 94.91 | 395 | 1090 |
| *May* | 95.00 | 94.62 | 7100 | 1510 |
| *Jun* | 95.00 | 95.00 | 0 | 0 |
| *Jul* | 95.00 | 94.98 | 0 | 44 |
| *Aug* | 95.00 | 94.79 | 740 | 667 |
| *Sep* | 95.00 | 94.45 | 6940 | 1320 |
| *Oct* | 95.00 | 93.42 | 8510 | 3630 |
| *Nov* | 95.00 | 83.70 | 8500 | 5250 |
| *Dec* | 95.00 | 85.46 | 9050 | **7750** |

The table illustrates that the maximum hydrogen tank level reached the upper limit defined by the control algorithm in all months while the minimum level was 16.13% in the first month of the simulation. The maximum power delivered to water electrolysis was in January of 9580 Watt. conversely, the maximum power requested from the fuel cell was 7750 Watt in December.

**Table 5-3 Maximum Values in the Battery System & PESS**

| *Month* | *max Battery Charging Power (W)* | *max Battery Discharging Power (W)* | *max Power generated by sources (W)* | *max Power delivered from ESS (W)* |
|---|---|---|---|---|
| *Jan* | 4430 | -3420 | 12380 | -6230 |
| *Feb* | 2620 | -1782 | 14720 | -2310 |
| *Mar* | 4960 | -2210 | 16590 | -2670 |
| *Apr* | 3520 | -3330 | 17240 | -3330 |
| *May* | 3369 | -2430 | 18030 | -2430 |
| *Jun* | 0 | -460 | 400 | -460 |
| *Jul* | 2720 | -3190 | **18150** | -3190 |
| *Aug* | 2819 | -2640 | 16830 | -2640 |
| *Sep* | 3630 | -2600 | 16770 | -2960 |
| *Oct* | 5200 | -3384 | 14560 | -4390 |
| *Nov* | 5600 | -3520 | 12240 | -5250 |
| *Dec* | **5680** | **-4660** | 10000 | **-7750** |

While this table emphasis more on the battery maximum charging and discharging power rates as well as the maximum power delivered and consumed by the energy storage system. The battery got the maximum rate of charge in December with a power of 5680 Watt slightly higher than its C rate and got highly discharged in the same month with a power rate of 4660 Watt below its capacity.

On the other hand, the renewable sources were generating higher power compared to the capacity of the energy storage system and the excess power above ESS limit is supplied to a dump load. The maximum power generated was 18.15 kW in July and the maximum power requested was 7750 Watt in December.

## 5.3 Fuzzy logic Controller Charging Scenarios

The purpose of this scenario is to emphasize the performance of the charging controller individually by fixing the supply power rate to a maximum of 10 kW and having zero demand load. Thus, the entire surplus power will be delivered to the energy storage systems. The other variable is the battery health status which will be between two statuses as excellent battery health status and poor battery health status.

The first scenario will have a 10 kW supply power with zero load and excellent battery health. The following figure shows the results of the controller behavior as well as the battery state of charge over the time.

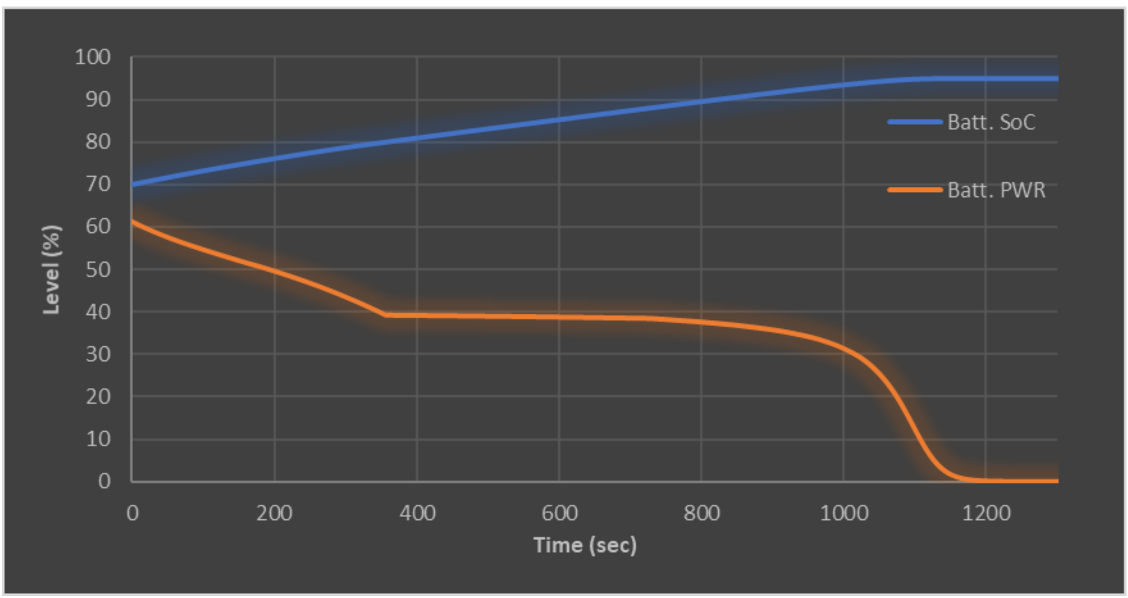


Figure 5-16 Charging battery with excellent battery health

As seen in the figure, the charging fuzzy logic controller distributes the power by considering the maximum battery charging power limit: slow charging power below 40% of total power when the battery state of charge above 80% and stop charging when $SOC_H$ is reached. Hence, the proposed FLC successfully achieved the goal of maintaining the battery under excellent health status.

The second scenario will have a 10 kW supply power with zero loads but this time the battery health is poor. The following figure shows the results of the controller behavior as well as the battery state of charge over the time.

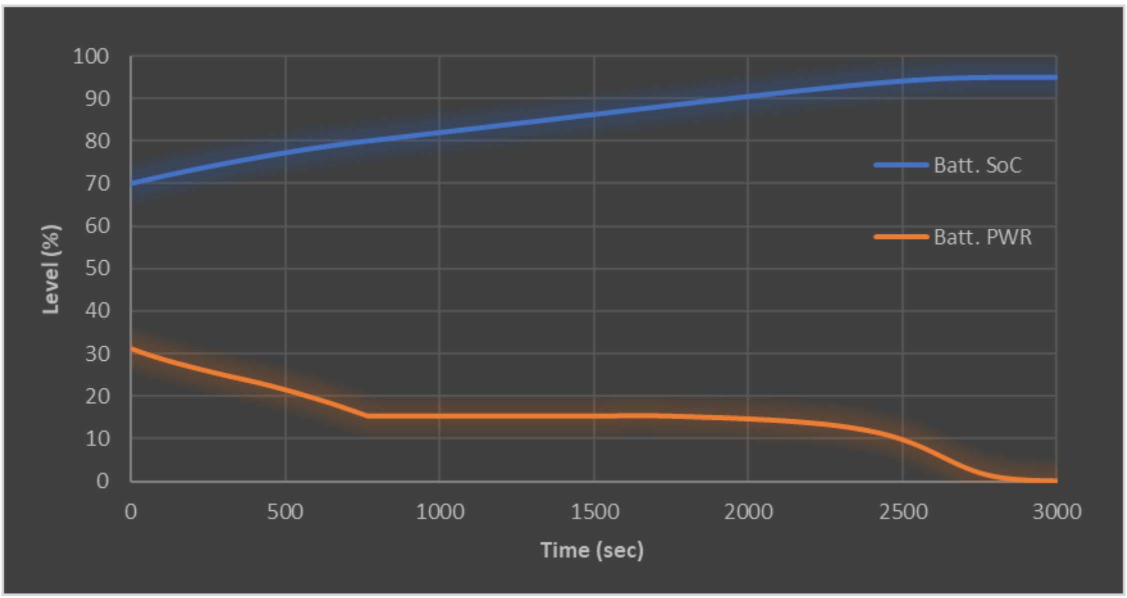


Figure 5-17 Charging battery with poor battery health

As depicted in the figure, the FLC acts in a more accurate and precise manner in making a decision for the charging of the battery. Hence, it assigns a small amount of power to $P_{ESS}$ to protect the battery from overcharging. That is, the FLC does not charge the battery with current higher than its maximum rate or charge the battery when it is at level $SOC_H$. Also, it can be seen that the controller slows the charging of the battery as its charge approaches $SOC_H$ level. With this ability of the proposed FLC, the objective of operating and protecting the battery in a proper manner is achieved.

## 5.4 Fuzzy logic Controller Discharging Scenarios

The purpose of this scenario is to highlight the performance of the discharging controller individually this time by fixing the house demand rate to a maximum of 10 kW and while having zero power supply. Thus, the entire needed power will be delivered from energy storage systems. The other variable is the battery health status which will be between two statuses as excellent battery health status and poor battery health status. The power required by the load is equivalent to the maximum discharging power of the battery, and the battery is under high stress.

Concurrently, the hydrogen controller will request the assigned power from the FC. However, if the tank is empty or the amount of power cannot be delivered from the FC or in the case of unhealthy FC, the hydrogen controller will request the system shutdown to avoid cascading effects. There are situations where the system is grid-connected or connected to another energy source, and in such case, an islanding phenomenon, which is beyond the scope of this work will occur.

The first scenario will have a 10 kW house demand with zero renewable sources and assuming the battery has an excellent health status. The following figure shows the results of the controller behavior as well as the battery state of charge over the time.

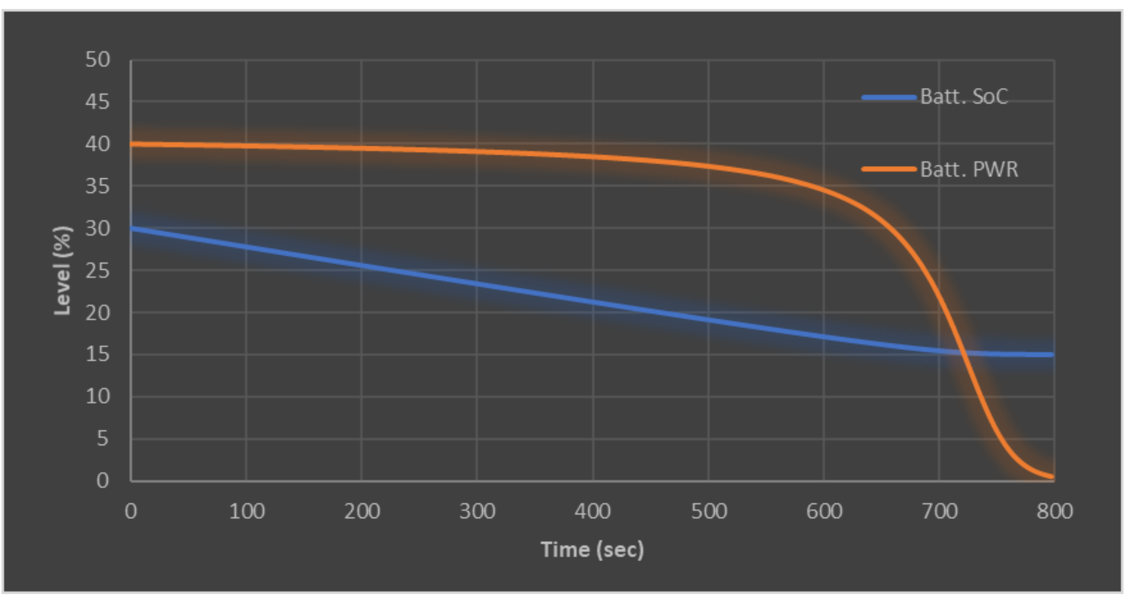


Figure 5-18 Discharging battery with excellent battery health

The power required by the load is equivalent to the maximum discharging power of the battery in 10KW, and the battery is under low stress. The proposed discharging fuzzy logic controller requests power from batteries and FC while protecting the battery and avoiding load supply deficiency. The above figure shows the discharging behavior of the battery. The FLC requests 40% of the power from the battery when the SOC is 30% and it decreases that percentage rapidly when the SOC is below 17%. Then, it stops requesting power from the battery when the charge level reaches $SOC_L$ and transfers the load to FC so that the power is supplied to the load by the FC alone.

The second scenario will have a 10 kW power demand with zero power supply but this time the battery health is poor. The following figure shows the results of the controller behavior as well as the battery state of charge over the time.

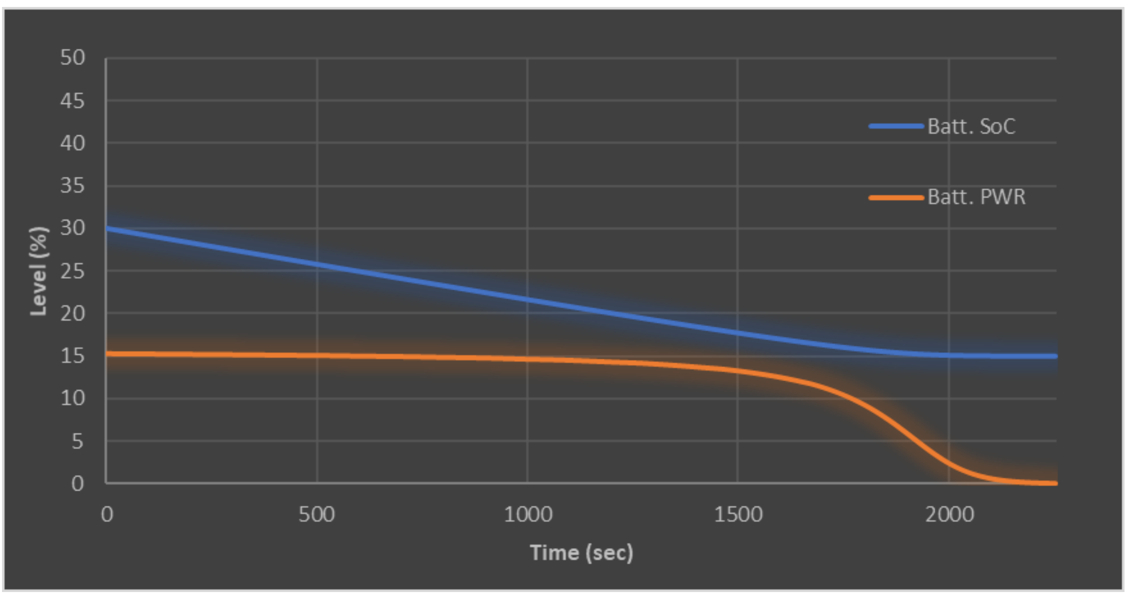


Figure 5-19 Discharging battery with poor battery health

The figure illustrates the smooth discharging effect of the battery. As shown in the figure, the proposed FLC minimizes the discharged power when the charge approaches $SOC_L$. This phenomenon begins at a point when the charge is below 20%. Thus, the FLC requests more power support from the FC than the battery. Hence in the discharging mode with 100% SPS and high battery stress status, the fuzzy logic proves to protect the battery from deep discharging, adequately meeting the required operating condition.

# 6. Conclusion

## 6.1 Conclusion

In this thesis, energy-related issues have been discussed and renewable energy is introduced as an alternative solution to minimize the financial and environmental effects of current energy sources specifically the ones relying on fossil fuels. Then The idea of the standalone power system is introduced and discussed. Out of that discussion, the necessity of having energy storage system is shown as the system is driven by renewable sources and those sources are affected by weather conditions which are nonlinear, non-predictable and highly variable. Using at least two kinds of energy storage systems and two kinds of renewable resources will strengthen the system and increase its reliability and stability. However, this kind of systems requires an intelligent controller to manage the power flow and sustain the system. In this thesis, a fuzzy logic based controller for HRES with multiple types of storage.

The proposed scheme solves the problem related to consumer needs by satisfactorily supplying the demand side while focusing on the safety of the lithium-ion battery system as well as its efficiency and reliability without a reduction in power quality. For more realistic results and comprehensive analysis of the proposed technique, real data of solar power wind power and load were applied to a smart power system modeled in MATLAB Simulink/Simpower Systems environment. With the proposed scheme, the power flow is adequately controlled. Excess power is accumulated by the storage system and the proposed fuzzy-based supervisory control provides the stability of the overall system. At the same time, it effectively manages the charging/discharging processes of the lithium-ion battery to extend its useful life. When needed, the proposed controller smoothly transfers the load the hydrogen system to avoid system failures and increase electrolysis and fuel cell lifespans.

All described modes were tested under multiple operating scenarios, and obtained results confirmed its capability to control HRES.

## 6.2 Future Work

Though the proposed scheme provides more desirable results, the following is recommended for future work. The application of the proposed FLC as a supervisory control in a more complex system including a larger network such as a smart grid system consisting of more than two areas is strongly recommended. On the other hand, it is recommended that small capacitors should be applied to mitigate infinitesimal power deficiency that can be observed. This power loss might seem to be negligible for small power systems, but as the system becomes larger and more complex, the loss might actually prove to be a significant amount, an expectation which needs to be verified.

## 6.3 Recommendation

One-day advance Forecast data, specifically designed behavior from operator to optimize the system, fuel cell controller that communicates with the main controller and after that the controller change its behavior.

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